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The Ohio State University  PH.D.  1980

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SCHEDULING OF VESSELS FOR SHIPMENT OF
BULK AND SEMI-BULK COMMODITIES
ORIGINATING IN A SINGLE AREA

DISSERTATION

Presented in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy in the
Graduate School of The Ohio State University

By

David Ronen, B.S., M.S.

* * * * *

The Ohio State University

1979

Reading Committee:

Dr. Bernard J. LaLonde
Dr. Robert G. House
Dr. LeRoy J. Krajewski

Approved by

[Signature]
Adviser
Department of Marketing
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And I want to thank my loving wife Miryam, who typed the numerous drafts and aided me along the way.
VITA

February 23, 1946 ...... Born - Haifa, Israel
1970 ..................... B.S.I.E., Technion-Israel Institute of Technology, Haifa, Israel.
1972 ..................... M.S.O.R., Technion-Israel Institute of Technology, Haifa, Israel.
1970-1973 .............. Teaching Assistant, Technion-Israel Institute of Technology.
1972-1973 .............. Research Associate, Israel Shipping Research Institute, Haifa, Israel.
1973-1975 .............. Lecturer, University of Haifa, Haifa, Israel.
1973-1976 .............. Deputy Head, R&D Division and Senior Projects Engineer, Maritime Fruit Carriers Co. Ltd., Haifa, Israel.
1976-1977 .............. Cargo Unitization Project Coordinator, Citrus Marketing Board of Israel, Tel-Aviv, Israel.
1977-1979 .............. Teaching and Research Associate, The Ohio State University, Columbus, Ohio

FIELDS OF STUDY

Major Field: Logistics
Minor Field: Production and Operations Management.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>ii</td>
</tr>
<tr>
<td>VITA</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
</tbody>
</table>

## I. INTRODUCTION

- Background ................................ 1
- Rationale for the Problem ................. 10
- Statement of the Problem .................. 14
- The Research Purpose ...................... 21
- The Research Questions ................... 23
- Scope ..................................... 23
- Methodology ................................ 24
- Limitations ................................ 26
- Potential Contributions ................... 28
- Organization ................................ 30

## II. LITERATURE REVIEW

- The Vehicle Scheduling Problem .......... 31
- Ship Scheduling Problems .................. 38
- Summary ................................... 42

## III. RESEARCH DESIGN

- Mathematical Programming .................. 46
- Random Generation of Solutions .......... 48
- Heuristic Programming ..................... 49
- Mathematical Formulations ................. 50
- Optimizing Algorithm for Small Problems . 51
- Random Generator of Schedules .......... 53
- Heuristic Algorithm ....................... 55
- Industry Scheduling Practice ............. 58
- Analysis of Policy Decisions .............. 59
Chapter III (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Cost Function</td>
<td>60</td>
</tr>
<tr>
<td>Experimental Design</td>
<td>62</td>
</tr>
<tr>
<td>Data Base</td>
<td>63</td>
</tr>
<tr>
<td>Summary</td>
<td>65</td>
</tr>
</tbody>
</table>

IV. THE FINDINGS .................................. 67

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Results</td>
<td>67</td>
</tr>
<tr>
<td>Comparison and Evaluation of Algorithms</td>
<td>78</td>
</tr>
<tr>
<td>Scheduling Cost Savings</td>
<td>82</td>
</tr>
<tr>
<td>Effects of Flexibility in Shipment Sizes</td>
<td>83</td>
</tr>
<tr>
<td>Effects of Limit on Number of Unloading Ports Per Vessel</td>
<td>87</td>
</tr>
<tr>
<td>Summary</td>
<td>89</td>
</tr>
</tbody>
</table>

V. SUMMARY AND CONCLUSIONS ...................... 90

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Research Problem</td>
<td>90</td>
</tr>
<tr>
<td>Research Purpose and Methodology</td>
<td>92</td>
</tr>
<tr>
<td>Results and Conclusions</td>
<td>94</td>
</tr>
<tr>
<td>Implications</td>
<td>96</td>
</tr>
<tr>
<td>Suggestions for Future Research</td>
<td>100</td>
</tr>
</tbody>
</table>

APPENDICES

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Mathematical Formulations</td>
<td>102</td>
</tr>
<tr>
<td>B. Optimizing Algorithm for Smaller Problems</td>
<td>110</td>
</tr>
<tr>
<td>C. Heuristic Scheduling Algorithm - Computer Program</td>
<td>112</td>
</tr>
<tr>
<td>D. Required Number of Random Schedules</td>
<td>124</td>
</tr>
<tr>
<td>E. Elements of Data Base</td>
<td>125</td>
</tr>
</tbody>
</table>

GLOSSARY OF TERMS ...................................... 128

BIBLIOGRAPHY ............................................. 130
LIST OF TABLES

Table | Page
--- | ---
2. Seaborne Trade of Dry Bulk Commodities | 5
3. Cost Structure and Control for a Shipper Under Various Operating Modes | 20
4. Summary of Major Vehicle and Ship Scheduling Models | 43
5. Experimental Design | 64
6. Results - Problem 1 | 68
7. Results - Problem 2 | 70
8. Results - Problem 3 | 72
9. Results - Problem 4 | 74
10. Results - Problem 5 | 76
11. Cost Savings Over Industry Practice | 80
12. Comparison of Total Cost of Schedules | 84
13. Effects of Flexibility Levels on Schedule Cost | 86
14. Effects of Limiting Number of Unloading Ports On Schedule Cost | 88
15. List of Ships and Their Employment Terms | 126
16. List of Ports | 127
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Advanced Planning Process</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>Operational Planning Process</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>Random Algorithm Flow-chart</td>
<td>54</td>
</tr>
<tr>
<td>4</td>
<td>Heuristic Algorithm Conceptual Flow-chart</td>
<td>57</td>
</tr>
<tr>
<td>5</td>
<td>Comparison of Algorithms - Problem 1</td>
<td>64</td>
</tr>
<tr>
<td>6</td>
<td>Comparison of Algorithms - Problem 2</td>
<td>71</td>
</tr>
<tr>
<td>7</td>
<td>Comparison of Algorithms - Problem 3</td>
<td>73</td>
</tr>
<tr>
<td>8</td>
<td>Comparison of Algorithms - Problem 4</td>
<td>75</td>
</tr>
<tr>
<td>9</td>
<td>Comparison of Algorithms - Problem 5</td>
<td>77</td>
</tr>
<tr>
<td>10</td>
<td>Comparison of Total Cost of Schedules</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>by Algorithms</td>
<td></td>
</tr>
</tbody>
</table>

vii
CHAPTER I
INTRODUCTION

Background

Since the Second World War the world has witnessed a remarkable expansion in trade\(^1\) which has reached the level of 1,280 billion dollars Free On Board\(^2\) in 1978,\(^3\) and which accounts for over 10 percent of the world's gross production.\(^4\)

International seaborne shipping is the major artery of international trade and it accounts for over 85 percent of the ton-miles,\(^5\) while air, truck, rail, and pipelines supply the balance. In 1976, 3,352 million tons of international trade were borne by sea, 1,797 million tons were


\(^2\) A glossary of terms is provided at the end of this work.

\(^3\) International Monetary Fund, *IMF survey*, February 19, 1979.

\(^4\) Lawrence, p. xiv.

\(^5\) Lawrence, p. 57.
tanker cargo,\textsuperscript{6} and the balance was dry cargo.\textsuperscript{7} It has been noted that the world economy is becoming increasingly dependent on the proper functioning of its sea transport component.\textsuperscript{8} Table 1 shows the increasing role of international seaborne trade and shipping relative to the world population. The table presents the changes in the world population, production, trade and shipping during the current decade. The size of the world merchant fleet in the middle of 1978 was 406 million Gross Registered Tons, or 670 million Deadweight Tons, consisting of 69,020 ships each over 100 GRT.\textsuperscript{9}

For shipping purposes, the industry differentiates the various components of international trade in terms of the physical and economic characteristics of the cargo and the size of the shipment, as well as in terms of trade routes. The seaborne trade is usually divided into the following groups:

\begin{itemize}
\item \textsuperscript{6}Crude oil and oil products.
\item \textsuperscript{8}Lawrence, p. xiii.
\item \textsuperscript{9}All world fleet statistics are based on Lloyds Register of Shipping, \textit{Statistical Tables 1978}, London, November 1978.
\end{itemize}
### Table 1: Growth Rates: World Production, Population, Trade and Shipping, 1970-1976

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>1970</th>
<th>1976</th>
<th>Annual Growth Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>World Population</strong></td>
<td>Index</td>
<td>100</td>
<td>112</td>
<td>1.9%</td>
</tr>
<tr>
<td><strong>World Domestic Product</strong></td>
<td>Index</td>
<td>100</td>
<td>128</td>
<td>4.2%</td>
</tr>
<tr>
<td><strong>International Trade</strong></td>
<td>Million U.S. $</td>
<td>279800</td>
<td>412300</td>
<td>6.7%</td>
</tr>
<tr>
<td>Export FOB: at 1970 prices</td>
<td>279800</td>
<td>412300</td>
<td>6.7%</td>
<td></td>
</tr>
<tr>
<td>Export FOB: at current prices</td>
<td>279800</td>
<td>896700</td>
<td>21.4%</td>
<td></td>
</tr>
<tr>
<td><strong>International Seaborne Trade:</strong></td>
<td>Million metric tons</td>
<td>1440</td>
<td>1797</td>
<td>3.8%</td>
</tr>
<tr>
<td>Tanker Cargo</td>
<td>1440</td>
<td>1797</td>
<td>3.8%</td>
<td></td>
</tr>
<tr>
<td>Other Cargo</td>
<td>1165</td>
<td>1555</td>
<td>4.9%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2605</td>
<td>3352</td>
<td>4.3%</td>
<td></td>
</tr>
<tr>
<td><strong>World Merchant Fleet:</strong></td>
<td>Thousand GRT</td>
<td>227490</td>
<td>372000</td>
<td>8.4%</td>
</tr>
<tr>
<td>Total</td>
<td>227490</td>
<td>372000</td>
<td>8.4%</td>
<td></td>
</tr>
<tr>
<td>Tankers</td>
<td>86140</td>
<td>168161</td>
<td>11.8%</td>
<td></td>
</tr>
<tr>
<td>Dry Bulk</td>
<td>46652</td>
<td>91738</td>
<td>11.9%</td>
<td></td>
</tr>
</tbody>
</table>

**Sources:**

1. Major bulk commodities—bulk commodities shipped in large volumes. These are oil and oil products, iron ore, coal, and grain.

2. Minor bulk commodities—bulk commodities shipped in smaller volumes, such as phosphate rock, sugar, potash, bauxite and alumina, manganese ore, salt.


4. Unitized cargo—containerized, palletized or on trailers.

5. General Cargo—relatively small shipment sizes without any common packaging pattern.

The items listed in the second and the third groups are only representative, and the division between these groups is not always clear-cut and often depends on the division's purpose.

The development of the seaborne trade of dry bulk commodities is presented in Table 2, which shows that the trade has been increasing but that the rate of growth depends on the specific commodity.

Due to the remarkable variety of cargoes, trade routes, and ownership, and because "The economic
### Table 2: Seaborne Trade of Dry Bulk Commodities

<table>
<thead>
<tr>
<th>Commodity</th>
<th>1970 Million metric tons</th>
<th>1970 Thousand million ton-miles</th>
<th>1976 Million metric tons</th>
<th>1976 Thousand million ton-miles</th>
<th>Annual Growth Rate (%)</th>
<th>Tons</th>
<th>Ton-miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron Ore</td>
<td>247</td>
<td>1,093</td>
<td>294</td>
<td>1,469</td>
<td>2.9</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>Grain</td>
<td>73</td>
<td>393</td>
<td>146</td>
<td>779</td>
<td>12.3</td>
<td>12.1</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>101</td>
<td>481</td>
<td>127</td>
<td>591</td>
<td>3.9</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>Bauxite and Alumina</td>
<td>34</td>
<td>99</td>
<td>42</td>
<td>158</td>
<td>3.6</td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td>Phosphate Rock</td>
<td>33</td>
<td>116</td>
<td>37</td>
<td>125</td>
<td>1.9</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Sugar</td>
<td>NA</td>
<td>NA</td>
<td>22</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Manganese Ore</td>
<td>NA</td>
<td>NA</td>
<td>9</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Softwood</td>
<td>NA</td>
<td>NA</td>
<td>54*</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Notes: NA - Data not available.

* - In million cubic meters.

advantage to be gained by achieving an optimum match of a ship and cargo is substantial,\textsuperscript{10} most oceangoing ships are of unique design.\textsuperscript{11} "Substantial variances are found in the costs of operating ships of various types, depending on the character of the ship itself, the trade in which it is employed, the flag of registry and the operating policies of the owner."\textsuperscript{12} Lawrence demonstrated these cost differences for various types of ships on a typical voyage, and showed that the cost per 1,000 tons of cargo can vary from $2.68 to $24.94.\textsuperscript{13}

In cases where shipping costs are high relative to the value of the commodity shipped, the relatively high costs tend to break the world into several distinct trading regions.\textsuperscript{14} Thus, voyage distances are reduced, and smaller size vessels are employed in such cases.

\textsuperscript{10}Lawrence, p. 84.

\textsuperscript{11}The author estimates that less than 30 percent of the oceangoing ships have sister ships, i.e., another ship of the same design.

\textsuperscript{12}Lawrence, p. 76.

\textsuperscript{13}Lawrence, p. 79.

The diversity of ship types and trades is accompanied by a wide range of operating modes and control terms. A shipper may use owned ships, ships on bareboat charter, time charter or voyage charter, or he may use the services of a shipping company through a contract of affreightment or its liner services. Each of these arrangements may have a variety of cost structures, and the specific terms are negotiated between the shipper and the shipowner.

An oceangoing ship is a major capital investment worth at least several million dollars, and its daily costs of crew, supplies, fuel, and capital may run into thousands of dollars, dependent upon the specific case.

Three broad categories of shipping services exist: liner, tramp and industrial. These classifications are not sharply defined, mutually exclusive, or recognized in international law. Liner companies bear many resemblances to U.S. domestic common carriers. The feature universally distinguishing liner from tramp companies is that the former advertise scheduled service between specified ports whereas the latter do not. Industrial operations are captive services in which both ships and cargoes are controlled by a single

---

15 Lawrence, p. 93.

entity. Ordinarily company-owned fleets are sized below their owners' basic, continuing requirements, and the fluctuations in transport needs are met by charters from other owners.

The tanker business strictly speaking represents only a specialized type of industrial and tramping operations, but because of its size is usually considered as a fourth group. Tankers, comprising 44 percent of the Gross Registered Tonnage of the world fleet, are only the most prominent of an increasing variety of specialized ships. Dry bulk carriers and combination, dry and liquid, bulk carriers account for 26 percent of the world fleet. Other specialized types of ships are unit load ships such as container ships and roll-on/roll-off ships, gas carriers and refrigerated vessels. Thus general cargo vessels account for less than 20 percent of the world fleet volume.

The character of seaborne trade flows has important implications for the organization of international shipping services. The handling of many cargoes can be expedited through investment in specialized facilities in the ports and onboard the ships serving the trade. When these cargoes move in sufficient volume to be handled by shipload lots they can provide the basis of a specialized service. The economies gained through moving shipload loads in special purpose ships may justify a shuttle
service with an empty return leg. Any single specialized movement is, of course, imbalanced by definition. Furthermore, the tendency of major bulk movements to originate either in extreme north latitudes, in the tropics, or from southern hemisphere nations, make it difficult to devise voyage itineraries which provide cargoes on the return leg from Europe, Japan and the U.S.

Ocean shipping is a truly international business. Ships are typically built wherever the most favorable arrangements can be made. They may be nominally owned by corporations, often holding a single vessel, formed solely for this purpose and domiciled wherever tax, registry, and national preference considerations may dictate. They may be managed by a professional management organization, by a charterer, or by both with respect to particular functions, and they are operated by the best available crews allowed under the laws of the registering nation.

This research analyzes a short term ship scheduling problem from the perspective of the industrial operator who ships dry bulk or semi-bulk commodities in bulk carriers, general cargo or refrigerated vessels. The author estimates that less than 20 percent of the tonnage of the world fleet is operated in such a manner. The scheduling problems of industrial shippers are different from those of shipping companies. The major concern of industrial
shippers is to ship their own cargo, whereas shipping companies solicit cargoes from other parties and try to maximize their profits.

Rationale for the Problem

For the purpose of this research scheduling of ships may be segmented into two categories:

1. Scheduling by shipping companies which do not own the cargo shipped on their ships, but may have service commitments to the shippers and usually solicit cargoes from shippers, and

2. Scheduling of ships controlled by the shippers themselves who ship their own cargo. These are usually large shippers who ship bulk or semi-bulk cargoes in large quantities.

Several reasons may induce producers to control the shipping of their products:

1. "Producers may feel . . . that their chances of capturing and retaining markets for their products are best served by a policy of CIF sales."\(^{17}\) This possibility applies mainly to exporters of perishable commodities such as citrus or bananas, who must control the shipping conditions in order to lengthen the shelf life of the produce, and to competitive trades such as potash or phosphate rock. These types of trades usually originate in a specific geographical area.

2. Inadequacy of available shipping services. When available shipping services are insufficient, either in their capacity, or frequency or quality of service, a producer who ships large quantities is compelled to assume the shipping of his product in order to assure timely delivery.

3. High freight rates. If a shipper conceives the freight rates to be too high he may undertake the shipping of his cargo in order to allow penetration to farther markets.

4. Laws and regulations of the origin countries: Producing countries, particularly in the third world, are now seeking a much more positive role in indigenous industry and to extend this to the area of transportation. . . . government sponsored ship building programs are increasingly in evidence . . . one must recognize a very legitimate desire to increase national flag participation in foreign trade, an aim which tends now to be backed by the imposition of cargo reservation policies or bilateral trade agreements or other, less direct, preferential legislation. This aspect of fleet ownership is becoming a very positive element in the trading environment for dry bulk carriers, nor is it limited to Third World countries, COMECON


19 Ibid.
nations also operating in a similarly protectionist manner.  

5. Vertical integration of operations.  
In a vertically integrated organization, the shipping of raw materials, intermediate products and finished products is usually operated by the organization itself, thus controlling the supply of inputs for its production and marketing operations. 

As a result of these trends "a growing proportion of the world bulk fleet is directly owned or associated with large cargo interests."  

For example, "Canadian forest products shipments are now mainly arranged on CIF terms, as are most Russian and Polish exports to Western Europe, and it is evident that an increasing proportion of all forest products sales are conducted on a CIF basis."  

Every shipping operator faces a scheduling problem. Since the daily variable cost of a ship is thousands of dollars, scheduling decisions involve large amounts of

---

21 Ibid. 
23 H.P. Drewry, Transport of Timber, p. 15.
money. The industry rule of thumb of sending the larger ship to the farther destination does not assure cost minimization. Most of the published work in ship scheduling deals with medium term scheduling of shipping companies. Although the medium term scheduling determines the fleet available for loading at any specific time, the operator who ships his own goods still faces the loading problem which is specified in this work. Results derived by Levy, Lvov, and Lovetsky show that, due to the high uncertainty in ship and port operations, the probability of meeting a planned quarterly shipping schedule is 0.3. When a ship misses the time for a scheduled operation it will most probably miss the following deadlines because due to the high daily cost of the ship, little or no slack is included in its schedule. Thus, the short term schedule, which is the subject of the study, is actually being carried out, but the medium term schedule serves more as a guideline which is undergoing continuous revision.


See Chapter II below.

Further suggestion of the significance of the problem is found in a private communication from Professor Zennon S. Zannetos who wrote: "The topic you chose is very challenging and I am glad to see that someone is trying to get hold of it."

This dissertation postulates that the literature has not dealt with the short term ship scheduling problem because of its complexity which renders it unfit to neat solutions, and because of the relatively low level of penetration of advanced quantitative analysis into the ocean shipping industry.

Statement of the Problem

This dissertation is concerned with a problem faced by the organization that ships by sea large quantities of a bulk or a semi-bulk commodity, or several such commodities which can be shipped together, from one origin area to many destination ports. Each port receives shipments of a relatively large size. Under these conditions a shipload may consist of shipments destined for several ports, and a shipment to a certain port can be split between several ships.

Based on sales forecast for the various markets, firm orders, production forecast, storage space availability,

27 Of the Alfred P. Sloan School of Management, Massachusetts Institute of Technology.
and handling capacity, a forecast of the required shipping space is being developed by the organization for several months or quarters ahead. With such advance notice the organization can make adjustments in the available shipping capacity in several ways:

1. Long term changes—which affect the fleet composition beyond 3-5 years, such as buying or selling ships, bareboat charters.

2. Medium term changes—which affect the fleet for several months up to 3-5 years, such as time charters, contracts of affreightment, securing liner space, sublets.

3. Short term changes—which has effect up to several months, such as voyage charters, ships delaying and extending time charters.

This advanced, or medium range, planning process is described in Figure 1. Due to the high uncertainty in shipping operations the medium range plan, which resulted in fleet capacity adjustments, serves mainly as a guideline.

A short term schedule, based on the fleet available for loading within one or two weeks, is needed in order to determine the actual scheduling of the ships available for loading during that period. This operational planning

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See Levy, Lvov and Lovetsky.
Figure 1: Advanced Planning (annually/semi-annually/quarterly)
process is outlined in Figure 2. The output of the operational planning process is the loading program which specifies for each ship the quantity to be loaded for every destination.

Sale commitments and forecasts combined with marketing and inventory policy, as well as existing stocks at the various stocking points and loading capacity, are translated into a short term shipping program—quantities to be loaded for the various destinations within one or two weeks. The shipping program has to be carried out by the shipping space available during that period, because no changes in the available shipping space are possible at such short notice. This work deals with the shipping space allocation problem.

The problem of this work is to assign the planned shipments, for a one-to-two week period, to the shipping space available during that period, in order to carry out the shipping program at minimum shipping and demurrage costs.

It is assumed that sufficient shipping space is available to carry out the shipping program. If not, the program should be reviewed and management should assign priorities to the various shipments.

The size of the available ships as well as their costs may vary widely. The various modes of operation of the vessels differ in the control the shipper has over the
Figure 2: Operational Planning (weekly/semi-monthly)
ships and in their cost structure. The modes are summarized in Table 3, which shows that when the shipper has control over a ship he either pays for it on a daily basis or per unit shipped, and he pays demurrage and port entry charges in both cases. The destination ports differ in their unloading rates and their port entrance dues; the latter are also a function of the ship size.

The study excludes from the scheduling problem ships whose route is predetermined as well as their cargo, since their costs cannot be changed. Under certain conditions, i.e., terms of contract of affreightment or a perishable commodity, the number of unloading ports per vessel may be restricted, and this restriction is incorporated into the problem formulation. Furthermore, due to draft or length limitations, terms of employment, or political reasons, certain ships may not be allowed to enter certain ports. These limitations are included in the formulation of the problem.

It is assumed that storage and handling constraints at the various ports are manifested in the shipping program; i.e., if a certain quantity is planned to be shipped to a destination port, it can be handled and stored there. The loading sequence, which is not determined by this work, can be used to regulate arrivals at destination ports. If several ships are being loaded for a certain port their
Table 3: Cost Structure and Control for a Shipper Under Various Operating Modes

<table>
<thead>
<tr>
<th>Mode of Operation</th>
<th>Daily Costs (at sea and in port)</th>
<th>Cost Per Unit Shipped</th>
<th>Port Entry Charge</th>
<th>Demurrage</th>
<th>Control Over Sailing Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owned Vessel</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Yes</td>
</tr>
<tr>
<td>Bare-Boat Charter</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Yes</td>
</tr>
<tr>
<td>Time Charter</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Yes</td>
</tr>
<tr>
<td>Voyage Charter</td>
<td>(?)</td>
<td>(?)</td>
<td>Y</td>
<td>Y</td>
<td>Yes</td>
</tr>
<tr>
<td>Contract of Affreightment</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Yes</td>
</tr>
<tr>
<td>Liner Space</td>
<td>N</td>
<td>Y(*)</td>
<td>N</td>
<td>N</td>
<td>No</td>
</tr>
</tbody>
</table>

Notes:  
Y - Yes, paid by the shipper  
N - No, not paid by the shipper  
(?) - Dependent on the specific charter party  
(*) - This cost is paid even if nothing is shipped in the secured liner space.
loading can be staggered so that they will not arrive together at that destination.

It appears that most shippers who control their fleet do not look for return cargoes. Due to the relatively high specialization of vessels and the trade imbalances, a return cargo at profitable rates is scarce and may often necessitate adding loading and unloading ports to the ships' itinerary. This situation causes some loss of control over the ships' scheduling and requires an increased fleet to accommodate all the shipments. By soliciting return cargoes the shippers actually become a shipping company and their priorities change. No transshipments are allowed because they are prohibitively costly for bulk or semi-bulk cargoes.  

The cost function which is minimized in this work consists of the cost of sea days of the ships, port days, port entry charges, unit shipping costs, return leg and demurrage, all according to the terms of employment of the specific ships.

The Research Purpose

The research has the following purposes:

1. To develop and examine three different methods, or tools, for scheduling of vessels for shipment

29 Lawrence, p. 81.
of bulk and semi-bulk commodities originating in a single area at minimum shipping and demurrage costs: a heuristic method, an optimal method and a random generator of schedules.

2. To compare the results of these three methods with the industry rule of thumb of sending the largest ships to the farthest destination.

3. To use the above mentioned tools to analyze the effect of the following policy decisions on the resulting cost of the assignment of the shipments to the vessels:

A. The maximum number of unloading ports per vessel. The shipper may impose a limit on the number of unloading ports per vessel in order to assure better consistency of delivery dates or to shorten the maximum transit time to the market in case of perishable commodities.

B. Allowed flexibility of shipment sizes. Shipments of bulk commodities are usually made on some continuous basis and a contract is not supplied in a single shipment. In such cases the quantities specified for the various destinations may vary within a certain range.
The Research Questions

The research attempts to answer the following questions:

1. Can vessels be scheduled at a total cost which is lower than the present industry practice?
2. What is the magnitude of possible cost savings?
3. Is biased random generation of schedules superior to a heuristic scheduling algorithm?
4. What is the effect on the scheduling cost of allowing flexibility in the planned shipment sizes?
5. How does imposition, by managerial policy decision, of a uniform upper limit on the number of unloading ports per vessel affect the scheduling cost?

Scope

The research is concerned with a problem faced by an organization which ships by sea a bulk or a semi-bulk commodity, or several such commodities which can be shipped together, from a single origin area to its own stores overseas or to customers which may be either manufacturing organizations or wholesalers. It does not deal with the problems of insufficient shipping capacity or customer service, and it is assumed that at least part of the available shipping capacity is under the shipper's control.
The research deals only with the problem of assigning the available shipping space to a given set of shipments at minimum total cost; it does not account for the dynamic effects of this assignment. For instance, if it is decided to load a ship when will she be available for next loading? And what about commitments to shipping companies?

The cost function which is minimized consists of the following costs of the available ships: cost of sea and port days, port entry charges, unit shipping costs, return leg and demurrage, all according to the terms of employment of the specific ships. This work does not allow cargo transshipments but does allow limiting ports of entry of specific ships.

Storage and handling constraints at the ports are not dealt with directly; they are assumed to be manifested in the set of shipments to be loaded. Loading and unloading sequences at the ports are not specified, and it is assumed that the shipper does not have backhauls from the unloading ports.

**Methodology**

A realistic data set which includes a set of destination ports, a set of shipments, and a set of ships with their associated characteristics, is constructed from industry sources and used for the tests and evaluations.
The research problem can be formulated as a mathematical programming cost minimization problem. For a mixed integer linear programming formulation the size of a realistic problem which may have several ships and several destinations is too large to be solved by existing computer codes. For problems in which the product of the number of destination ports by the number of available ships is less than 25, a decomposable mixed integer non-linear formulation is used to find the optimal solution through implicit enumeration. A heuristic algorithm based on single step cost minimization and savings approaches is developed, along with a random generator of schedules which selects the cheapest schedule out of many randomly generated schedules.

The quality of the results derived by the heuristic and the random algorithms is tested on the one hand by comparing the results to the industry practice, and on the other hand, by comparing them to the optimal schedule for the smaller size problems. For the larger problems, the results are compared to the industry practice and to lower bounds on the value of the solution. The lower

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31 The limit of 25 is due to computer time requirements only.
bounds are achieved by solving the mixed integer linear formulation of the problem\(^{32}\) while dropping the integer requirements.

The effects of the following policy variables on the solutions are tested:

1. Maximal number of unloading ports per vessel.
2. Allowed flexibility in shipment size.

The cost function which is minimized consists of six components: cost of sea days, cost of time in port at the unloading ports, unit shipping costs, port entry charges, empty return leg, and demurrage.

**Limitations**

One of the major limitations of the research is evident from its name; that is, it deals with shipments originating in a single area. Although this limitation may sound strict, many organizations ship minerals or agricultural produce from a single loading zone to many destinations. Even organizations which load in many origin areas face the single loading zone problem if the origins are widely separated.

The proposed approach does not take into account the dynamic effects of the decision to load or not to use a ship in the planning period. This decision may determine

\(^{32}\)See Appendix A, Formulation 1.
when the specific ship will be available next time for loading, where the ship is owned or under bareboat or time charter. Since the uncertainty in the turnaround time of a ship arises from many sources, estimation of this dynamic effect is complex and unreliable. Further aspects omitted from the problem are delivery and redelivery dates of time chartered vessels and possible flexibility in them, as well as possible flexibility in due dates of the shipments, and commitments to shipping companies. It is assumed that these aspects are reflected in the shipping program and in the constraints on the available vessels.

The research deals with a short term ship scheduling problem which is faced by one sector of the ocean shipping industry, namely, industrial operators who ship dry bulk and semi-bulk commodities originating in a single area. In the sector selected for analysis characteristics of ships and products do not cover the full array of the

33 Ships may be delayed due to weather conditions, strikes, mechanical troubles and port handling problems like congestion or break-down of specialized handling equipment.


35 These commitments are quantity schedules in contracts of affreightment.
technology, and the results should be interpreted accordingly.

The optimizing algorithm provides an optimal solution to smaller size problems, but it does not allow flexibility in shipment sizes. The heuristic and random algorithms provide solutions which are not necessarily optimal but they can solve larger and more realistic problems.

**Potential Contributions**

The major potential contribution of the research is a methodology for determining a shipping space allocation for a fleet of vessels, which vary in their physical characteristics as well as in their cost structure and terms of employment. This methodology tries to minimize the shipping costs of a set of shipments and the demurrage cost of unused shipping capacity.

Managerial contributions--The daily cost of a ship is thousands of dollars and the scheduling decision which is analyzed in this work may involve hundreds of thousands of dollars weekly. The present practice of the industry is to look for a feasible schedule guided by a rule of thumb.\(^{36}\)

\(^{36}\)The rule of thumb is: Send the largest ships to the farther destinations. This rule is aimed at minimizing the shipping costs, which are only part of the total cost. The logic behind this rule is this: Since larger ships are generally more expensive, sending them to farther destinations increases the share of sea days in their voyage. Sea days are considered the productive part of the voyage. Thus the more expensive ships are more productive.
The new methodology results in remarkable financial savings to the shipping organization, even if percentagewise these savings may be relatively small.

Methodological contributions--The problem of this work is an extension of the vehicle scheduling problem, which has been discussed in the literature. The vehicle scheduling problem deals with scheduling, under a set of constraints such as truck capacity or route length, a fleet of trucks for delivery of a set of shipments to many destinations from a central depot. The objective of the vehicle scheduling is to minimize the mileage or time travelled by the trucks. The vehicle scheduling problem assumes that the trucks are identical costwise and that they all return to the depot. However, in this work's problem every vessel may have a different cost structure, not all of them return to the origin, a destination may be supplied by more than one vessel, and the objective is to minimize a total cost function rather than the distance or time travelled. Thus, the problem solved in this work is a realistic extension of the vehicle scheduling problem, and has not been treated in the literature.

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Mileage or time travelled are actually proxy variables for variable costs when all the trucks have the same cost function. A review of the vehicle scheduling problem is provided in Chapter II.
Organization

The balance of the dissertation is presented in Chapters II through V. Chapter II contains the literature review of the vehicle scheduling problem, an extension of which this research deals with, and a review of ships scheduling problems. Chapter III presents the research design, describes the various scheduling algorithms used in the research and their theoretical background, and outlines the data collection process. The findings of the research are presented and analyzed in Chapter IV. In Chapter V the conclusions are developed and their implications are evaluated. Also future research directions are indicated.
CHAPTER II
LITERATURE REVIEW

The objective of this chapter is to survey the literature relevant to the problem which this study treats. Since the scheduling problem with which this work deals is an extension of a problem which is known in the literature as the vehicle scheduling problem, a review of the vehicle scheduling problem and the various approaches to its solution is presented. The second section of the chapter reviews various ship scheduling problems and proposed approaches to their solution. The last section provides a comparative summary of the major scheduling models presented in this chapter and discusses the differences between these models and the problem of this research.

The Vehicle Scheduling Problem

The vehicle scheduling problem is concerned with scheduling vehicles from a central depot for delivery or pick-up of a single commodity at many points. The required schedule minimizes either the total mileage covered by the vehicles or their total travel time, while supplying all the demand at the given points, under a set of constraints. Constraints may include time or distance limits on vehicle
route length or vehicle capacity constraint. Another constraint would be that certain vehicles may not visit certain points.

The routes of the vehicles start and end at the depot. It is often assumed that all the vehicles are identical in their capacity and costs, and then mileage or travel time minimization is identical to variable cost minimization. It is further assumed that every requirement is smaller than the vehicle capacity; thus a single visit to a point supplies its demand.

The unconstrained problem which requires only that all the points are visited and all units return to the origin, is known as the travelling salesman problem. It has been treated often in the literature, but no procedure has been found to solve optimally a large travelling salesman problem.\(^1\) The difficulty is that the single depot vehicle scheduling problem "may be formulated in integer linear programming terms, but the number of variables precludes the solution of such a model."\(^2\)


The vehicle scheduling problem was first formulated by Dantzig and Ramser, who solved the problem of gasoline delivery from a bulk terminal to service stations by using equal size trucks. They tried to minimize the total mileage of the trucks and used an algorithm based on linear programming logic to obtain near optimal solutions. Clarke and Wright improved the Dantzig and Ramser algorithm and extended it to the case where the trucks may have different capacities, but they still try to minimize the total mileage of the trucks without accounting for their different costs. The Clarke and Wright approach is based on a "savings" logic: it begins with one truck going to each demand point and then drops trucks by adding their points to routes of other trucks, according to a cost savings criterion. This approach has been the basis for several commercial computer programs for the vehicle scheduling problem. Gaskell compared several variations


5Wren and Holliday, p. 334.

of the Clarke and Wright method on several test problems and showed that none of the variations was uniformly superior.

Christofides and Eilon\(^7\) considered the vehicle scheduling problem with vehicle capacity constraints and route length constraints. Their objective is to find the minimal number of vehicles that gives a feasible solution, and for that number of vehicles to minimize the total distance of the tours. They applied observations on optimal solutions of the travelling salesman problem to the vehicle scheduling problem, and developed a new method which generates a random initial solution and tries to improve its routes. The random initial solution is generated many times and the best results are selected. Christofides and Eilon compared their approach with the branch-and-bound approach which guarantees an optimal solution to the integer linear formulation of the problem, and with the "savings" approach of Clarke and Wright. Christofides and Eilon claim that their method is the best one.

O'neil and Whybark\(^8\) dealt with the vehicle scheduling


problem without capacity constraints, but with route length constraints, and tried to minimize total travel time. They proposed several additional heuristics: clustering customers combined with travel time saved, the closest customer heuristic, the farthest customer heuristic, and biased random selection of customers. They compared these heuristics with the "savings" approach and concluded that the latter was the most promising. Further extensions to the Clarke and Wright "savings" approach were investigated by Tillman and Cochran, and Holmes and Parker.

Gillet and Miller introduced a "sweep" algorithm to solve the capacitated vehicle scheduling problem. The "sweep" algorithm first segments the demand points into routes by sweeping them with a ray from the depot, and then tries to find the optimal route within every segment by solving a travelling salesman problem. Gillet and Miller compared their "sweep" algorithm to the "saving" algorithm


and to the Christofides and Eilon approach; they claim that the "sweep" algorithm is superior for large problems.

Golden, Magnanti and Nguyen\textsuperscript{12} discussed various integer programming formulations of the vehicle scheduling problem, analyzed the "savings" and "sweep" heuristic approaches and extensions of them, and introduced computer algorithms to improve the solutions.

Foster and Ryan\textsuperscript{13} combined elements of the "sweep" algorithm and the Christofides and Eilon approach; they suggested a solution to the vehicle scheduling problem by assigning vehicles to feasible routes through an integer programming formulation. They reduce the size of the problem by considering only routes which serve all deliveries in a sector and do not cross themselves or other routes. This last approach does not seem applicable to large problems due to the size of the integer program.

Crawford and Sinclair\textsuperscript{14} applied the Foster and Ryan approach to scheduling beer trucks. They solved the


integer problem as a linear problem and rounded the results to receive integer values.

Recently, Cunto\textsuperscript{15} scheduled boats to sample oil wells with time and number of points constraints per route by using a procedure similar to the "sweep" algorithm which first generates routes and in a second stage tries to improve them. His problem included hundreds of wells and priorities were given to wells in case the fleet of boats was insufficient to sample all of them. The objective was to sample maximum number of higher priority wells while minimizing total travel time.

An extension of the single depot vehicle scheduling problem is the multiple depots problem, which has been heuristically dealt with by Wren and Holliday,\textsuperscript{16} Gillet and Johnson\textsuperscript{17} and Golden, Magnanti and Nguyen\textsuperscript{18}.

The problem of scheduling ships has been dealt with in the literature from several aspects, and is reviewed in the following section.

\begin{flushright}
\textsuperscript{16} Wren and Holliday, p. 340.
\textsuperscript{18} Golden, Magnanti and Nguyen, p. 142.
\end{flushright}
Ship Scheduling Problems

In contrast to the vehicle scheduling problem, where the structure of the problem was similar and only the constraints were sometimes changed, scheduling of ships has been dealt with in the literature from several perspectives, which resulted in different problem formulations.

The ship scheduling problem most widely discussed is presented by Dantzig and Fulkerson. 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. The problem was solved as a transportation problem and the tankers' schedules were derived from the solution. Briskin 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. A problem similar to that of


Dantzig and Fulkerson was solved by Flood. \textsuperscript{21} Since he assumed a given size fleet of identical tankers, he minimized the total empty distance of the ships by solving a transportation problem.

Bellmore, Bennington and Lubore\textsuperscript{22} further extended the problem by considering different tanker capacities 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 with a branch-and-bound algorithm. However, no results have been presented. Hartley and McKay\textsuperscript{23} added realistic dimensions to the tanker scheduling problem by considering multiple products and excluding entry of certain ports by certain tankers due to draft or length limitations. They used a heuristic algorithm, with a mathematical programming subroutine for utility maximization, to select a schedule from a set of acceptable routes.


Although this last work is the most realistic one, it still assumes that the shipment sizes are smaller than the vessel sizes, i.e., a requirement is filled by a single ship.

A different medium term ship scheduling problem was dealt with by Laderman, Gleiberman and Egan, who presented a linear programming model for scheduling a fleet of vessels for transportation of bulk commodities in ship loads from a set of origins to a set of destinations. Non-integer number of voyages was rounded in this model. This problem is faced by a shipping company which undertakes to carry out contracts of affreightment. Whiton introduced further practical handling capacity constraints to this last problem. A similar problem was discussed by Rao and Zions, who allowed also chartering vessels for trips, but still considered only operating and chartering costs, not demurrage expenses.


Olson, Sorenson and Sullivan\textsuperscript{27} were concerned with
the scheduling problems of a shipping company operating
liners between the U.S. West coast and Hawaii, and analyzed
them by a computer simulation model which included heur­
istic decision rules.

Applegren\textsuperscript{28} dealt with a medium term scheduling prob­
lem of an operator who has a combination of tramp cargoes
and contracts of affreightment. His objective was to
maximize the profit from optional cargoes while carrying
all contracted cargoes, allowing only one shipment per trip.
Applegren's model used linear programming with decomposition,
which does not guarantee integer solutions.

Shechter\textsuperscript{29} presented a ship scheduling problem which
is similar to the vehicle scheduling problem. He dealt
with collection of cargoes to a central transshipment point
and used a heuristic opposite to that of Clarke and Wright.

\textsuperscript{27}C.A. Olson, E. E. Sorenson and W. J. Sullivan,
"Medium Range Scheduling for Freighter Fleet," Operations
Research 17 (July 1969): 565-582.

\textsuperscript{28}Lief H. Applegren, "A Column Generation Algorithm
for a Ship Scheduling Problem," Transportation Science 3
(Feb. 1969): 53-68.

\textsuperscript{29}Joel Shechter,"A Minimum Cost Vessel Routing Model
Applied to the U.S. Trust Territory of the Pacific Islands,"
He began with one vessel making all the pick-ups and added vessels until he achieved a solution accounting for the vessel capacity constraint. Still, total distance of the vessels was minimized and all vessels return to the origin.

**Summary**

Table 4 summarizes the major transportation scheduling models which have been discussed in this chapter. Due to the combinatorial size of the problems and their discrete nature, almost all the models use combinations of heuristics and optimization methods, and therefore cannot guarantee an optimal solution.

It is noted that most of the ship scheduling models described above deal with the medium range scheduling problem. Results derived by Levy, Lvov and Lovetsky show that the probability of meeting a planned quarterly shipping schedule is 0.3 due to high uncertainty in shipping and port operations. Thus, the short term schedule, which is the subject of this research, is the one which is actually being carried out whereas the medium term schedule serves more as a guideline.

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Table 4: Summary of Major Vehicle and Ships Scheduling Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Identical transport units</th>
<th>Single visit per destination</th>
<th>Single destination per voyage</th>
<th>Route length constraint</th>
<th>All units return to origin</th>
<th>Unit capacity constraint</th>
<th>Exclusion of destination entries</th>
<th>Identical cost for all units</th>
<th>Delay/queue considered</th>
<th>Planning Range</th>
<th>Objective</th>
<th>Optimal Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Traveling Salesman</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Problem</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Short</td>
<td>Min. distance</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>Vehicle Scheduling</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Dantzig &amp; Ramser</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Short</td>
<td>Min. distance</td>
<td>Y</td>
</tr>
<tr>
<td>Clarke &amp; Wright</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Short</td>
<td>Min. distance</td>
<td>N</td>
</tr>
<tr>
<td>Christofides &amp; Eilon</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Short</td>
<td>Min. distance</td>
<td>N</td>
</tr>
<tr>
<td>Gillet &amp; Miller</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Short</td>
<td>Min. distance</td>
<td>N</td>
</tr>
<tr>
<td>Ship Scheduling</td>
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<td></td>
</tr>
<tr>
<td>Dantzig &amp; Fulkerson</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Medium</td>
<td>Min. units</td>
<td>N</td>
</tr>
<tr>
<td>Hartley &amp; McKay</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Medium</td>
<td>Max. Utility</td>
<td>N</td>
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<tr>
<td>Laderman,</td>
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<tr>
<td>Gleiberma &amp; Egan</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Medium</td>
<td>Min. cost</td>
<td>N</td>
</tr>
<tr>
<td>Applegren</td>
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<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Medium</td>
<td>Profit</td>
<td>N</td>
</tr>
<tr>
<td>Shechter</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<td>Y</td>
<td>N</td>
<td>Short</td>
<td>Min. distance</td>
<td>N</td>
</tr>
<tr>
<td>This Research</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Short</td>
<td>Min. cost</td>
<td>S</td>
</tr>
</tbody>
</table>

Notes: S = Only for smaller size problems
N = No
Y = Yes
The problem of this work differs from the vehicle scheduling problem as treated in the literature in the following points:

1. Ships are different from each other in their capacity; speed and cost structure.
2. Not all the ships return to their origin.
3. An unloading port may be supplied by several ships.
4. Total cost minimization is considered.

Zannetos referred to a different aspect of the specific problem of this research:

Given a fleet of small and large tankers, how many people, for example, would intuitively accept that there are certain tanker sizes and runs for which it is better to assign the larger tankers for the shorter runs and the smaller tankers for the longer runs. For resolution of this paradox one must look at the relative advantages of the larger over the smaller tankers during periods of idleness versus running. Note that as posed, this is an overall cost minimization problem.31

In this research, actual costs of idleness versus running are considered, and the overall cost minimization problem is dealt with under a set of realistic constraints.

The following chapter presents the various algorithms used in this research, their theoretical background and

description. In addition, the experimental design and the data base are presented.
CHAPTER III
RESEARCH DESIGN

The purpose of this chapter is to present the methodology of the research in a manner that facilitates acceptance or rejection of the research questions.

The first part of this chapter is devoted to the description of the research tools developed in this work. First, the theoretical background to mathematical programming, random sampling of solutions and heuristic programming are discussed. A description follows of the algorithms used in this work: the optimizing algorithm, the random generator of schedules, the heuristic algorithm, and the industry practice algorithm. The second part of the chapter presents the design of the research. The policy decisions which are analyzed are described, the various components of the cost function are discussed, and the experimental design and the data base are presented.

Mathematical Programming

A mathematical programming problem consists of four components: technical coefficients, decision variables, costs of decision variables, and levels of constraining variables. All these are organized in a set of constraints and an objective function.
The technical coefficients specify the weights of the decision variables in the constraints, and the costs have the same role in the objective function; both coefficients and costs, as well as the levels of the constraining variables, are provided as input data. The decision variables are the unknowns of the problem, and the constraints specify physical limitations on values of the decision variables. The value of the objective function has either to be minimized or maximized, as applicable.

A solution to a mathematical programming problem is a set of finite values to the decision variables. A feasible solution satisfies all the constraints of the problem. An optimal solution gives an extreme value to the objective function, minimum or maximum, as applicable, and is a feasible solution. The objective in solving a mathematical programming problem is to find an optimal solution. An optimal solution to a problem where some of the original constraints have been relaxed cannot be worse, i.e., higher for a minimization problem or lower for a maximization problem, than an optimal solution to the original problem. Therefore, the value of an optimal solution to the relaxed problem is a bound on the value of the optimal solution to the original problem.

Many types of mathematical programming problems have been defined, and algorithms for their optimal or near
optimal solutions have been formulated. A major type is the linear programming problem, in which the constraints and the objective function are linear functions of the decision variables. An extension of the linear programming problem is the mixed integer linear problem, in which part of the decision variables can take only integer values. The size of a problem is measured by the number of the decision variables and the number of the constraints. Linear programming problems with thousands of variables and constraints can be solved by existing computer codes. Generally, a mixed integer linear problem with several hundred integer variables cannot at present be solved optimally within a reasonable computer time frame, unless the problem has a specific structure which may be used to formulate a specialized algorithm for its solution. "Mixed integer linear programs . . . with several hundred integer variables have been undertaken, but usually the result has been a suboptimal feasible solution."¹

Random Generation of Solutions

With the increase of computing power and speed, random sampling has become a method for generating solutions to complex problems. Random sampling has been used for problem with the following characteristics: large

combinatorial size, complex objective function, and computationally inefficient exact solution procedures. For such problems, random generation of many solutions allows the researcher to choose the best. Sampling quickly produces solutions which are nearly optimal, but their distance from the optimum is not known.

Heuristic Programming

An examination of the relevant literature reveals the wide range of concepts included in the word "heuristic" as applied by various authors. This work adopts McMillan's definition: "A heuristic program is a computational procedure which, when applied to any one of the class of problems for which it is applicable, will yield a good solution in a finite number of steps." A good review of heuristic programming is provided by Michael. He states:


The heuristic approach is ideally suited to two types of problems, those that are too large for traditional operations research models and those that are too loosely structured or ill-structured to be expressed in the mathematical terms necessary for the traditional algorithmic models.

Heuristic programming saves computation time for large problems. Furthermore, heuristic programming is flexible enough to be applied to ill-structured problems. The disadvantage of heuristic programming is the difficulty in evaluating its results; that is, since it does not guarantee an optimal solution, the value of the solution it provides is questionable. Since the optimal solution is usually not known, the value can be determined relative to bounds on the optimal solution, or to existing practice of solving the problem. This research compares the heuristic solution to the industry practice and to the optimal solution, when the latter is known, and to a lower bound on the optimal solution when it is not.

Mathematical Formulations

Two mathematical formulations of the deterministic problem are provided in Appendix A. Formulation 1 is a mixed integer linear program which results in a large size problem. If there are $P$ destination ports and $S$ ships, this formulation has $SP \cdot (P+1)$ binary variables, $SP$ continuous variables, and $5S + P + 3PS$ constraints. This formulation is used with the requirement for binary values
on the decision variables relaxed, to obtain a lower bound on the value of the objective function. This is done in order to compare this bound to the solutions obtained by the heuristic and random algorithms developed in this work.

Formulation 2, is a decomposable non-linear program. This formulation has SP binary and SP continuous variables. The formulation allows decomposition of the problem into two parts: a routing problem which determines the value of the binary variables, and a loading problem. Once the routing of the ships is known, i.e., the values of the binary variables are determined, the loading problem, a generalized transportation problem, is left to be solved. Formulation 2 is the basis for the optimizing algorithm for smaller problems which is developed in this work.

**Optimizing Algorithm for Smaller Problems**

The algorithm discussed here is based on formulation 2 in Appendix A. This algorithm uses the specific structure of the problem as formulated in formulation 2 for implicit enumeration of the solutions space. Once the routing of the ships is known, i.e., the values of the binary variables are determined, the loading problem—a generalized transportation problem—is left to be solved.

---

The algorithm checks all the possible feasible routings, solves the corresponding loading problems, calculates the total cost in each case, and selects the solution with the minimal overall cost. Theoretically, when there are $S$ ships and $P$ unloading ports there are $SP$ routing decision variables. Each variable can be either zero or one. Thus, possible routings amount to $2^{SP}$, a big number for a practical problem.

Taking into account the following characteristics of the problem, the number of routings to be calculated is reduced remarkably:

1. If there are shipments to $P$ ports, at least $P$ port entries must be in the routing, i.e., at least $P$ ones must be in a routing combination.

2. The capacity of vessels entering a port must be larger than the quantity destined for that port.

3. If there is a constraint on the number of unloading ports per vessel the routing must satisfy it.

4. For a given routing the generalized transportation problem will result in no more than $S + P$ positive loadings, i.e., $S + P$ port entries, and port entries without cargo to unload can be cancelled. Therefore, only routings with $S + P$ or less port entries should be considered, i.e. no more than $S + P$ ones in the routing combination.
Once a routing is defined, the generalized transporta-
tion problem is solved by assigning high costs to port
entries which are not included in the routing. Then port
entries without cargo are eliminated from the routing and
the cost of the solution is calculated. The cost of sea
days of every ship is calculated by choosing the shortest
route through its unloading ports.

The algorithm is provided in Appendix B. Due to
limitations on computer time requirements, this algorithm
is practical to problems in which the product SP is up to
25, and less than 30 minutes of CPU time is required on an
Amdahl 470 computer.

Random Generator of Schedules

The random generator of schedules used in this work
uses the uniform distribution for the selection of ships
and unloading ports, i.e., every ship has the same proba-
bility of being chosen and every unloading port has equal
probability of being chosen. A flow chart of the random
algorithm is provided in Figure 3.

The algorithm chooses a ship at random and assigns
to it unloading ports at random until the ship is full or
the limit on the number of unloading ports for the ship
has been reached. The choice probabilities are dynamically
updated according to the number of unallocated ships or
ports which are left, as applicable. After allocating
Figure 3: Random Algorithm Flow - Chart

Start

Read Data

Any Empty Ships?

Load The Ship To The Port

Yes

Select a Ship At Random

Any Cargo Left?

Yes

Select an Unloading Port At Random

Limit on No. Of Ports For This Ship Exceeded?

Yes

Ship Port Capacity Demand

Load The Ship To The Port

No

No

Yes

Calculate Shortest Route for Every Ship, Total Cost of Schedule, Compare & Store

Last Iteration

Yes

Print Cheapest Schedule

Stop

Initiate Next Iteration
all the shipments to the ships the algorithm calculates for every ship the shortest route through its unloading ports and then calculates the cost of the solution. This procedure is repeated many times and the cheapest schedule is selected.

A lower bound on the total number of possible different randomly generated schedules is $S!P!$, where $S$ is the number of ships and $P$ is the number of unloading ports. Due to the shortest route calculation, each randomly generated schedule represents the best schedule out of a set of possible schedules. In order to be 99% confident that the solution is in the cheapest 0.1% of all the possible schedules, 4,598 schedules are generated and the lowest cost one is chosen.

**Heuristic Algorithm**

A heuristic algorithm is developed for solving the problem presented in this study. The heuristic algorithm tries to minimize cost per ton-mile of cargo. Since a given set of shipments, according to their sizes and destinations, specifies the required cargo ton-miles to be performed by the fleet, the shipping cost per cargo ton-

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7 More schedules are possible if a port is served by more than one ship.

8 See Appendix D.
mile—the output unit—is a good basis for comparison between possible vessel voyages. A conceptual flow chart of this algorithm is presented in Figure 4. Listing of the computer program of this algorithm is provided in Appendix C.

At the initial stage of the algorithm the cost of the cheapest possible voyage for every port is calculated according to the available fleet. This minimum cost voyage for each port serves later as a benchmark for assigning ship voyages to that port.

At the scheduling stage the algorithm takes the ships which have not been assigned yet, beginning with the most constrained ones, according to the following order: first, ships which are allowed less unloading ports, and, within this classification, ships which are excluded from more unloading ports. The algorithm tries to assign the ships to the unloading ports, from the farthest port to the nearest one, as long as the cost of the cheapest voyage to that port is less than the cost criterion. First, single unloading port voyages are considered for all the ports, and later two, and then three, unloading ports voyages are evaluated, if applicable. The cost criterion is defined in terms of cost increase over the minimum cost voyage to every port. When the cost criterion is, for example, 0.2, cheapest voyages the cost of which is up to 20% higher than the minimum cost voyage to the specific port are being assigned to that port.
Start

For every port calculate the cheapest single unloading port voyage

Set initial cost criterion

Take ships from most constrained
Take ports from farthest to nearest

Increase cost criterion

is cost criterion at upper limit?

Yes

Increase initial cost criterion Generate a new schedule

No

Are all shipments assigned?

Yes

Is current schedule cheaper than the former one

Yes

Have there been five schedules with different initial cost criteria?

Yes Print cheapest Schedule

No

No

Decrease initial cost criterion, Generate a new schedule

Figure 4: Heuristic Algorithm Conceptual Flow-Chart
The first scheduling begins with an initial cost criterion of 0.1, and the cost criterion is gradually relaxed until a schedule is achieved. All cost comparisons are on cost per ton-mile of cargo basis. At least five schedules with different initial cost criteria are generated. The initial cost criterion is increased by 0.15 over the one of the last schedule if that schedule did not improve the scheduling cost, and decreases by 0.05 if the last schedule was the cheapest one found. Within a scheduling process the cost criterion is increased in steps of 0.5 up to value of 10.0. If no schedule is obtained the scheduling begins again with an increased value to the initial cost criterion.

As long as the cost of the obtained schedules is decreasing, further schedules are generated, thus more than five values to the initial cost criterion may be examined. The minimum cost schedule generated is selected.

The results derived by this algorithm are compared to the industry practice and the results of the other algorithms used in this work.

Industry Scheduling Practice

The industry scheduling rule of thumb is to send the largest ship to the farthest port. The industry scheduling algorithm is tailored to this rule. This algorithm sends the largest ship to the farthest port and, in case the
ship is not full, adds unloading ports nearest to the former one, till the ship is filled up. The results of this algorithm serve as a benchmark in the evaluation of the results of the heuristic and random algorithms.

Analysis of Policy Decisions

Management can make certain policy decisions which may affect the resulting shipping space allocation. The major two policy decisions are:

1. Upper limit on the number of unloading ports per ship—increasing this limit may result in increased computation time, but may decrease the cost of the schedule.

2. Flexibility in shipment size—due to the nature of the bulk and semi-bulk trades, which very often involve shipments on a continuous basis, there may be some tolerance in the shipment sizes. Changes within a certain range may be allowed in the specified quantities to the various destinations.

The first policy decision may be incorporated into the optimizing algorithm, and the two of them can be dealt with by the heuristic and the random algorithms.

The effects of these two policy decisions on the cost of the resulting schedule is tested.
The Cost Function

The cost function considered in this work is the sum of six components: cost of sea days of ships, cost of port days of ships at the unloading ports, unit shipping costs from the origin to the destination, port entry charges for the unloading ports, demurrage costs for ships not used during the planning horizon, and cost of sea days of empty return leg, all as applicable to the terms of employment of the specific ships available during the planning horizon.

The cost of port days of the ships at the loading port is not included since it is assumed that every ship which is at the loading port will have to load sooner or later. The port entry charges of the loading port are disregarded also, since every ship will have to enter and load.

The daily cost of an owned ship at port is the operating cost which includes the costs of manning, insurance, repair and maintenance, stores and administration, plus the capital cost of the vessel. The daily cost at sea for an owned vessel is the daily cost at port plus the cost of the fuel and oils needed for steaming. The daily demurrage cost of an owned vessel is equal to its daily cost at port. Unloading port entry charges include the actual port entry charge, which depends on the size of the
ship, and the cost of ship's time lost in long pilotage and waiting for a berth.

For chartered ships the costs are those specified in their contracts, usually a daily cost paid to the shipowner, plus those cost components paid directly by the shipper, such as port entry charges and fuel costs.

Certain contracts, mainly contracts of affreightment or voyage charters, may specify a unit shipping cost from the origin to every unloading port. In such cases no daily costs exist, except demurrage, but certain cost components such as port entry charges may still be paid directly by the shipper and should be taken into account, as applicable.

Liner space is excluded from the analysis because, at short notice, its cost is a sunk cost, and it should be used as long as the demurrage cost of the non-liner space is lower than the shipping cost of that non-liner space. It is inconceivable that the demurrage cost for a vessel will be higher than its shipping cost.

The cost minimized is the cost of the decision made, i.e., the shipping costs of the set of shipments plus the demurrage cost of the unused ships till the next planning period.
Experimental Design

Four different scheduling methods are compared on a set of different problems, as applicable. The four methods are:

1. The industry practice of sending the larger ships to the farther unloading ports, and filling-up the ship by entering adjacent unloading ports.
2. Random generation of many feasible schedules and selection of the best one.
3. The optimizing algorithm, for smaller size problems, which is described above, and, in detail, in Appendix B.
4. The heuristic algorithm which is described above, and in Appendix C.

In addition, bounds derived from the relaxed mixed integer linear formulation, which appears in Appendix A, are calculated as a reference point to the various solutions.

The problems solved by these methods differ in the following aspects:

1. Problem size—number of ships available and number of destination ports. Five problem sizes are solved, two smaller size and three larger size. The problem sizes are: 5 ports x 3 ships, 6 x 4, 8 x 7, 10 x 10, and 12 x 12.
2. Allowed flexibility in shipment sizes—three levels of flexibility are explored: no flexibility, \(\pm 10\%\) of shipment size and \(\pm 20\%\).

3. Maximal number of unloading ports allowed per ship—two levels of this variable are used: 2 and 3 unloading ports per vessel.

Table 5 summarizes the methods, their limitations, and the number of problems to be solved by each.

The results achieved by the various methods are compared on the basis of two variables:

1. The cost of the derived schedule.
2. Computer time required to obtain the schedule.

Data Base

A realistic data base is constructed from published industry sources and estimates. The data base includes data about 20 ships under various employment terms, and 20 ports and distances between them. The ships and the destination ports for each of the five test problems solved in this work are selected from this data base. The shipment sizes for each of the five problems range from several thousand tons to tens of thousands tons.

The data for every vessel includes: capacity, speed, draft, fuel consumption, mode of operation, and the relevant costs. The data for every destination port consists of: distance to all other ports, unloading rate,
<table>
<thead>
<tr>
<th>Method</th>
<th>1 Industry</th>
<th>2 Heuristic</th>
<th>3 Random</th>
<th>4 Optimal</th>
<th>5 Bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limitation</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>small problems</td>
<td>no flexibility</td>
</tr>
<tr>
<td>Problem sizes</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Flex. levels</td>
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<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ports limits levels</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Number of problems to solve</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>4</td>
<td>10</td>
</tr>
</tbody>
</table>
port entry dues for every vessel, draft limitation, port congestion, and long pilotage in terms of time loss.

The distances between ports are extracted from distance tables.\(^9\) The ships are selected from contracts reported by industry sources,\(^10\) and their physical characteristics are found in a ships' register.\(^11\) Data concerning ports is extracted from ports directory.\(^12\) All costs are converted into US dollars which serve as the financial common denominator. Major elements of the data base are provided in Appendix E.

Port entry charges are in the range of thousands of dollars. These charges may be much higher if congestion exists in the ports because they should include the cost of the ships' time waiting for discharge. In this work it is assumed that there is no congestion at the various ports.

**Summary**

The four different scheduling methods used in this work, as well as their theoretical background, were


presented in this chapter. The four methods are an optimizing algorithm for smaller problems, a random generator of schedules, a heuristic algorithm and the industry practice. Later, the objective function, the experimental design, and the data base were discussed.

The following chapter presents the results of the experiments and answers the research questions.
CHAPTER IV

THE FINDINGS

The findings of the research are presented in this chapter. First, the results of the application of the various algorithms on the five test problems are presented; then, based on these results, the algorithms are compared and evaluated. Later, the remaining research questions are discussed and answered on the basis of the results of the application of the various scheduling algorithms to the five test problems. The five problems differ mainly in their size and represent a realistic range of practical operations. Cost comparisons are done on the cost per million ton-miles of cargo, which is the output unit, and is thus the basis for comparison between the costs of schedules with different outputs.

The Results

The costs of the schedules derived by the various algorithms used in this work, as well as the computer time required to run them, are presented in Tables 6 through 10 and Figures 5-9. Each table and the corresponding figure include results for one test problem. All the results were derived by computer programs run on The Ohio State University Amdahl 470V/6 computer. The programs for the
Table 6: Results - Problem 1 (3 Ships, 5 Unloading Ports)

<table>
<thead>
<tr>
<th>Flexibility</th>
<th>Max. No. of Ports</th>
<th>1 Industry</th>
<th>2 Heuristic</th>
<th>3 Random</th>
<th>4 Optimal</th>
<th>5 Bounds</th>
</tr>
</thead>
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<td></td>
<td></td>
<td>2 100</td>
<td>4 92</td>
<td>7 85</td>
<td>12 85</td>
<td>1 59</td>
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</tr>
<tr>
<td></td>
<td></td>
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<td>4 87</td>
<td>6 86</td>
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<td>NA</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 100</td>
<td>3 85</td>
<td>6 78</td>
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<td>7 88</td>
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<td></td>
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<td>4 91</td>
<td>6 86</td>
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<tr>
<td></td>
<td></td>
<td>2 100</td>
<td>4 94</td>
<td>6 86</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Cost per mil. ton-miles ($)  
CPU (sec.)  Cost Index  

NA - Not applicable
Figure 5: Comparison of Algorithms, Problem 1
### Table 7: Results - Problem 2 (4 Ships, 6 Unloading Ports)

<table>
<thead>
<tr>
<th>Flexibility</th>
<th>Max. No. of Ports</th>
<th>Algorithm</th>
<th>Algorithm</th>
<th>Algorithm</th>
<th>Algorithm</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>1 Industry</td>
<td>2 Heuristic</td>
<td>3 Random</td>
<td>4 Optimal</td>
</tr>
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<td></td>
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<td></td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>2 100</td>
<td>4 98</td>
<td>6 71</td>
<td>NA</td>
</tr>
</tbody>
</table>

**Cost per mil. ton-miles (\$)**

**CPU (sec.)**

**Cost Index**

NA - Not applicable
Figure 6: Comparison of Algorithms, Problem 2
Table 8: Results – Problem 3 (7 Ships, 8 Unloading Ports)

<table>
<thead>
<tr>
<th>Flexibility</th>
<th>Max. No. of Ports</th>
<th>Algorithm</th>
</tr>
</thead>
<tbody>
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<td></td>
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Cost per Mil. Ton-Miles ($)
CPU (sec.)  . Cost Index
Figure 7: Comparison of Algorithms, Problem 3
Table 9: Results - Problem 4 (10 Ships, 10 Unloading Ports)

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Cost per mil. ton-miles ($)
CPU (sec.) Cost index
Figure 8: Comparison of Algorithms, Problem 4.
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<td>5 88</td>
<td>20 80</td>
</tr>
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</table>

Cost per mil. ton-miles ($)
CPU (sec.)  Cost index
Figure 9: Comparison of Algorithms, Problem 5.
algorithms of the industry practice, the heuristic and random algorithms, and the optimal algorithm were written by the author. The bounds were derived by using MPS360 software package by IBM for solving linear programming problems. All running times are given in total CPU seconds.

The values of the bounds turned out to be more than 30 percent lower than the value of the corresponding optimal solutions. This difference renders them meaningless for comparison purposes, so the bounds were not calculated for all the problems. The reason for the low quality of the bounds lies in the fact that the values of the binary variables, which define the routing of the vessels, determine a relatively large share of the total cost of the schedule. Thus, relaxing the binary requirement on the routing variables drives the resulting bound far from the optimal solution.

Comparison and Evaluation of Algorithms

For comparative purposes the costs in Tables 6-10 are translated into an index, where the cost of the industry practice schedule for the same case is the basis, i.e., the denominator.

In all the 30 variations of the problem which were run, both the heuristic and the random algorithms provide schedules with costs lower that the industry practice. In 27 of these cases the random algorithm outperforms the
heuristic one, and the heuristic algorithm provides the lowest cost schedule in only three cases. The optimal schedule is calculated for four of the cases, and in three of these four the same schedule is supplied by the random algorithm. But it should be stressed that this is true only for the smaller problems. For larger problems it is expected that the random algorithm will less often provide the optimal solution, due to the larger number of possible routes combinations.

The range, in percents, of the cost savings of the heuristic and random algorithms in comparison to the industry practice is presented in Table 11. The superiority of the random algorithm to the heuristic one is obvious from these results, although, as mentioned above, it is not uniformly superior. As stated in Chapter III, the random algorithm is built to provide, at 99% confidence, a solution the cost of which is in the lower 0.1% of the costs of all the possible solutions. Thus, the best solution out of 4,598 solutions is chosen, and this fact is reflected in the results.

The amount of computer time required to run the algorithms varies according to the algorithm and size of the problem. The times for the heuristic algorithm ranged from 3 to 5 seconds, whereas the random algorithm took 6-7 seconds in the smaller problems, and up to 24 seconds
Table 11: Cost Saving Over Industry Practice (Range in Percents)

<table>
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<tr>
<th>Problem No.</th>
<th>Algorithm</th>
<th></th>
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</thead>
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<td></td>
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<tr>
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<td>5</td>
<td>12 - 22</td>
<td>16 - 21</td>
</tr>
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</table>
in the larger ones. The optimal algorithm is applied only to small problems, due to its computer time requirements, and this requirement is very sensitive to the constraints on the problem. Reducing the maximum number of unloading ports allowed per vessel from three to two reduced the computer time requirement for the optimal algorithm by about 60%.

The distribution of the 4,598 schedules which were generated in every run was derived while applying the random algorithm to the test problems. It was observed that the distribution of the random schedules has a bell shape, truncated on both ends. The ratio of the standard deviation over the average was in the range 0.049-0.128. The lowest cost schedules in the two smaller size problems, problems 1 and 2, were 2.08 to 3.20 standard deviations below the corresponding averages. In the other problems, where a much smaller share of the possible combinations was covered by the 4,598 random schedules, the cheapest schedules were between 3.01 and 3.92 standard deviations below the corresponding averages. It should be stressed, again, that the random schedules which were generated are not totally random, due to the shortest route calculation for every ship through its unloading ports, and that therefore the distribution of the random schedules is biased and does not necessarily represent the distribution of all possible schedules.
In each run the heuristic algorithm generated between 1 and 3 different schedules; in most instances there were 2. In 80 percent of the runs the first schedule generated was the best one; this share was lower in the smaller problems and higher in the bigger problems. Although the heuristic algorithm has a potential for generating very good solutions, its performance is not uniform. This flaw is attributable to the single step cost minimization logic, which does not look forward and therefore leaves bad options for the later stages, where the choice of scheduling alternatives is more limited. The results and uniformity of performance of the heuristic algorithm can probably be improved by randomly choosing ports for assignment of cheapest voyages, instead of scanning the ports from the farthest to the nearest, then choosing the best schedule from many generated with the same initial cost criterion, and only later changing the cost criterion. Such a change introduces a random element into the heuristic algorithm and may improve it significantly.

**Scheduling Cost Savings**

From a short look at Table 11 it is clear that scheduling can be done at a cost lower than the industry practice. Remarkable cost savings can be achieved by using the scheduling algorithms developed in this study. In comparison to the industry practice the heuristic algorithm
brings cost savings of 2 to 25 percent and the random algorithm results in savings of 12 to 34 percent.

The total cost of the schedule can be compared between algorithms if the same sizes of shipments are shipped, i.e., if no flexibility in shipment size is allowed. This comparison is provided in Table 12 and Figure 10. The range of attainable savings on a weekly basis is from tens of thousands of dollars in the smaller size problems to hundreds of thousands in the larger size problems.

**Effects of Flexibility in Shipment Sizes**

When flexibility in shipment sizes is allowed, one may generally expect a lower cost schedule due to elimination of port entries to unload small quantities, and better space utilization of ships. The effects of allowed flexibility levels on the cost of the schedules are presented in Table 13. For easier interpretation, the data is presented as an index where the cost of the case without flexibility is the basis. For example, if the cost of the case without flexibility is 7,972 and the cost of the case with flexibility of 0.1 is 7,695, the entry in the table for the latter case will be \((7,695/7,972) \times 100 = 97\).

Although the results generally show reduced schedule cost with higher flexibility, many irregularities appear, especially in the heuristic algorithm, due to the discrete
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Notes: NA - Not applicable  
NC - Not calculated
Figure 10: Comparison of Total Cost of Schedules
Table 13: Effects of Flexibility Levels On Schedule Cost (Cost Index)

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</table>

Note: Cost of the same problem and the same Algorithm and Max. No. of ports, without flexibility = 100.
nature of the problem and the nonuniform behavior of the algorithm, as discussed above. The expected decrease in the schedule cost due to increase in flexibility is hard to evaluate from these results since it depends also on the specific case. An increase in flexibility from 0.0 to 0.1 resulted in cost decrease of up to 5 percent in the random algorithm where three unloading ports per vessel were allowed, and up to 12 percent where only two were allowed. The corresponding figures when the flexibility is increased from 0.0 to 0.2 are 12 and 14 percent.

Effects of Limit on Number of Unloading Ports Per Vessel

When the upper limit on the number of unloading ports per vessel is reduced, it is expected that the schedule cost will increase because some of the schedules are no longer feasible. The effects of reducing the maximum number of unloading ports per vessel from three to two are presented in Table 14. The data presented in the table is the ratio, in percents, between the cost of the two ports limit schedule and the three ports limit schedule. If, for example, the cost of the three ports limit schedule is 7,972 and the cost of the two ports limit schedule is 7,904, the entry in the table will be \((\frac{7904}{7972}) \times 100 = 99\). Due to the discrete nature of the problem and the structure of the algorithms, some entries in the table are less than 100. The behavior of the random algorithm is more stable
Table 14: Effects of Limiting Number of Unloading Ports On Schedule Cost (Cost Index)

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</table>

Notes: Cost of the same problem with maximum of 3 unloading ports = 100.
All data presented is for the case with maximum of 2 unloading ports.
NA - Not Applicable
than that of the heuristic algorithm. It can be seen that in most cases the costs do increase due to the tighter constraint, but the magnitude of the increase depends on the specific problem. In most cases the results of the random algorithm show cost increases in the range of 0 to 3 percent.

Summary

The objective of this chapter has been to present the findings of the research. It was shown that the random generator of schedules is usually superior to the heuristic algorithm and that both reduce the schedule costs remarkably in comparison to the industry practice. The cost savings over the industry practice may accumulate to millions of dollars annually, dependent upon the size of the operation. Allowed flexibility in shipment sizes further reduces the cost of the schedule, but the magnitude of the reduction depends on the specific situation. An increase in the upper limit on the number of unloading ports per vessel does generally reduce the schedule cost, but, again, the size of the reduction depends on the specific situation.
The Research Problem

The continuous increase in the world population and its standard of living is accompanied by higher consumption of natural resources, and with the exhaustion of available local resources the international trade and sea transport of such resources is growing. Various economic and political reasons compel producers to sell their goods on CIF terms, where the seller looks after the shipment of the commodity. Increasingly protectionist cargo reservation policies of developing and communist countries stimulate this trend toward CIF sales.

The problem analyzed in this research is one faced by a shipper who controls a fleet of vessels and ships a bulk or a semi-bulk commodity in large quantities from a single origin area to many destinations. As a result of the shipper's policies and prior decisions concerning marketing, inventories, production and loading capacities and fleet size, he faces a short term planning problem: how to load the shipments planned for the next week on the ships available for loading during that period, in order to ship those shipments at minimum shipping and demurrage costs.
This problem is the subject of the research.

The problem is an extension of the vehicle scheduling problem but here the total cost is minimized rather than distance or travel time, the transportation units have different sizes and cost structures, a demand point may be served by several units, and not all the units return to the origin.

Five research questions are posed in this work:

1. Can vessels be scheduled at a total cost lower than the industry practice?
2. What is the magnitude of possible cost savings?
3. Is biased random generation of schedules superior to a heuristic scheduling algorithm?
4. What is the effect on the scheduling cost of allowing some tolerance in the planned shipment sizes?
5. What is the effect on the scheduling cost of limiting the number of unloading ports per vessel?

The set of shipments is defined by their sizes and destinations. At such a short notice no changes in the available fleet are possible. The available ships may differ in their size, speed, terms of employment and cost structure.
The total cost function which is being minimized consists of six components: Cost of sea days of the ships, cost of port days of the ships at the unloading ports, port entry charges, cost of empty return legs, unit shipping costs and demurrage, all as applicable to the terms of employment of the specific ships.

The destination ports differ in their unloading rate and their port entry charges; the latter depend also on the size of the ship. A shipment to a certain port may be split between several ships, and a ship may unload in several ports, but the number of unloading ports per ship may be restricted. For various reasons certain ships may not be allowed to enter certain ports. Cargo transshipments are not allowed since they are prohibitive costwise for bulk or semi-bulk cargoes.

Research Purpose and Methodology

The first purpose of the research is to develop and examine three different methods for solving the scheduling problem specified above: a heuristic method, a random generator of schedules, and a cost minimizing optimal method. A second purpose is to compare the results derived by these methods to the industry practice of sending the larger ships to the farther destinations. The third purpose is to use the tools developed in the research for analysis of the effects of the following two management policy decisions on
the costs of the resulting schedules: The allowed maximum number of unloading ports per vessel, and allowed flexibility in shipment sizes.

Four different scheduling methods are used in the research. First, an optimizing algorithm, based on a mixed integer non linear mathematical program of the problem, is used to find the optimal minimum cost schedule to smaller size problems. Second is a heuristic algorithm, based on sequential single step cost minimization logic. A random generator of schedules, which randomly generates many schedules and selects the cheapest one, is the third. The results of these three methods are compared to the cost of schedules derived by the industry practice algorithm. In addition, a mixed linear integer formulation of the problem is used, while relaxing the integer requirement, to achieve lower bounds on the value of the optimal solution.

Five test problems of different sizes are solved, each with three different shipment size flexibility levels, and two different bounds on the number of unloading ports per vessel. Every problem is solved by all the applicable methods out of those outlined above.

The analysis is based mainly on the costs of the derived schedules, but computer time requirements of the various algorithms are compared too. The data for the test problems is drawn from a data base which is constructed
from data in published industry sources and estimates.

Results and Conclusions

In all the 30 cases solved, both the heuristic and the random algorithms gave cheaper schedules than the industry practice. In 90 percent of these cases the random algorithm outperformed the heuristic one. In three out of the four cases where the optimal schedule was derived, the random algorithm resulted in the optimal schedule. The lower bounds on the costs of the schedules turned out to be more than 30 percent lower than the value of the optimal solution; thus they were useless for purposes of comparison. The random algorithm performs so well for two reasons. First, it chooses the best schedule out of many schedules, and second, the schedules generated are not totally random. The schedules are biased due to the shortest route computation for every vessel. The heuristic algorithm does not give good solutions, although it has the potential for them, and its performance is not uniform. The non-uniform behavior is attributable to the discrete nature of the problem and to the single step cost minimizing logic, which does not look forward and thus often leaves bad options for later scheduling stages. These deficiencies may probably be overcome by introducing some random mechanism into the heuristic algorithm, and then selecting the best schedule out of many generated.
Although not uniformly superior to the heuristic algorithm, the random generation of schedules is the better one. It should be used when the optimal schedule cannot be found due to excessive computer time requirements.

The answer to the first research question is definitely positive. Scheduling can be done at a cost lower than the industry practice. The size of the achievable schedule cost reductions is remarkable, from 2 to 34 percent, dependent upon the specific case and the algorithm used. In financial terms the savings range from tens of thousands of dollars for the smaller problems, to hundreds of thousands for the larger, all on a weekly basis.

The fourth research question addresses the issue of flexibility in shipment sizes. An increase in the allowed flexibility level for shipment sizes generally reduces the cost of the derived schedule, but the size of the reduction depends on the specific case and the algorithm used. An increase of the flexibility level from 0 to 10 percent resulted in cost reductions of up to 12 percent with the random algorithm, and an increase from 0 to 20 percent resulted in cost reductions of up to 14 percent with the same algorithm.

The last research question looks at the effect of limiting the number of unloading ports per vessel. Decreasing the maximal number of unloading ports per vessel from
3 to 2 does generally increase the cost of the schedule, but the size of the cost increase depends, again, on the specific case and the algorithm used. With the random algorithm the cost increases are up to 9 percent.

Implications

The results derived in the research demonstrate the cost savings which can be achieved by applying quantitative methods to scheduling problems in the capital intensive shipping industry. Even small savings percentagewise accumulate to respectable amounts when the daily cost of a ship is thousands of dollars. Some organizational obstacles may be confronted while trying to improve the decision making process through the application of more advanced quantitative methods, but with proper attention these obstacles may be averted or overcome.

The use of rule of thumb, which may be logical, do not necessarily result in good solutions, especially when the logic of the rule of thumb is based on premises which are not necessarily true. The wide variety of ship designs and operating terms combined with sharp cost fluctuations in the shipping market renders such rule of thumb less applicable to the shipping industry. Moreover, rules of thumb are usually designed to reduce the cost of only one component of the total cost, and do not look at the whole cost of the decision. The discrete nature of the
scheduling problem further reduces the effectiveness of rules of thumb since they do not look forward.

The research shows that various elements can be combined in the solution of the short term ship scheduling problem. Loss of ships' time due to port congestion can be included in the cost of port entrance and thus accounted for. Demurrage charges for the ships that are not used are incorporated in the cost function as well as the cost of unloading time of the ships that are used. Thus, scheduling decisions may now be done on the basis of all fleet related costs and not only sailing costs. Further practical operational considerations, such as tolerance in shipment sizes and limit on the number of unloading ports per vessel, are introduced into the solution of the problem. Operational constraints, such as exclusion of entry to certain ports by certain ships, are also incorporated in the solution. Few authors have realized the importance of the short term ship scheduling problem, and this research is probably the most comprehensive effort to solve the problem while taking into account many realistic aspects of the problem which have not been treated in earlier research. The algorithms used in this research can be used in practical situations and can be modified to provide several good schedules to the scheduler.
When scheduling decisions are made alternative schedules should be evaluated on the basis not only of sailing costs, but of their total cost to the operator, which includes demurrage charges, port entry dues, port congestion, and cost of ships' unloading time.

The shipping operator should evaluate trade-offs between policy decisions and their effects on the costs of the operation. When negotiating sales agreements the management should consider inserting clauses which allow it certain flexibility in the shipment sizes, because such flexibility may significantly reduce the scheduling costs. When hiring ships it should be borne in mind that increasing the limit on the number of unloading ports per vessel does reduce the schedule cost somewhat, although the magnitude of the reduction is hard to estimate.

The complexity of the scheduling cost function, combined with the discrete nature of the ship scheduling problem which has been dealt with in this work, caused non-uniform performance of the heuristic algorithm. Although the heuristic algorithm has potential for generating good solutions, they are very often mediocre because the algorithm does not look forward. Incorporation of randomizing procedures into the heuristic algorithm may improve its performance. When the optimal solution is not available, selection of the cheapest schedule, out of many randomly
generated, appears to be the best approach to ships scheduling.

The short term ship scheduling problem which has been treated in this research is an extension of the vehicle scheduling problem. Several restrictive assumptions which are usually included in the vehicle scheduling problem have been relaxed here. In this problem the transportation units may have different capacities, and different cost functions. Here a demand point is not necessarily supplied by a single visit and not all the units are required to return to the origin. Moreover, here a total cost function is minimized rather than time or distance of travel. Thus the vehicle scheduling problem is a specific case of the problem treated here. Past research did not consider most of these extensions. It is evident that all the above mentioned extensions introduce more realistic dimensions to the vehicle scheduling problem.

Real scheduling problems are not as neat as they appear in the literature and therefore they often require specialized solutions. Operational uncertainties, which are usually ignored in the literature, may play a substantial role in reality, and in certain instances may necessitate a real-time scheduling system. Medium range plans which determine the fleet capacity and composition are not the ones which are actually carried out, and the need for
operational planning exists in every shipping scheduling operation.

Suggestions for Future Research

The problem which is the subject of this research is an extension of the vehicle scheduling problem to the ocean shipping area. Most of the published work in ship scheduling deals with medium range scheduling which, due to the relatively high uncertainty in ship operations, is appropriate to address the problems of fleet size and mix. However, this research focuses on the short term scheduling which is actually being carried out.

One of the possible directions of future research is to explore the relations between the medium and the short range scheduling problems. On the one hand the medium range plan dictates the available fleet. On the other hand, once a ship is loaded by the short range plan, it is not available for loading for at least the next several periods, until it returns back to the loading port.

A second research direction may be to allow different flexibility in shipment sizes to every unloading port. This is a more realistic version of the problem and relatively easy to explore by changing the appropriate parameters in the computer programs.

Other modifications may consider the possibility of return cargoes, either from the unloading ports or from
other ports, and certain ships which must end their voyage in a specific port or range of ports due to their contract requirements. Judging from the results of this research, it seems that the random generation of schedules is the most promising approach by which to investigate these extensions.
The research problem can be formulated mathematically in several ways. Two formulations are presented here and the resulting problems are discussed.
Formulation 1 - Mixed Integer Linear Program

Indices:

\[ i, j \in J \] - Set of ports (0 is the origin)
\[ k \in K \] - Set of ships

Decision variables:

\[ X_{ijk} = \begin{cases} 
1 & \text{If vessel } k \text{ goes from port } i \text{ to port } j. \\
0 & \text{Otherwise} 
\end{cases} \]

\[ Z_{jk} = \begin{cases} 
1 & \text{If the final destination of vessel } k \text{ is port } j \\
0 & \text{Otherwise} 
\end{cases} \]

\[ Y_{jk} \] - The share of the shipment for port \( j \) which is loaded on vessel \( k \).

Data:

\( C_k \) - capacity of vessel \( k \)
\( V_k \) - speed of vessel \( k \) (nautical miles per day)
\( S_k \) - daily cost of vessel \( k \) at sea.
\( P_k \) - daily cost of vessel \( k \) at port
\( \alpha_{kj} \) - the cost of shipping a unit of cargo on vessel \( k \) to port \( j \) (from the origin)
\( D_k \) - demurrage cost of vessel \( k \) (for the planning period)
\( d_{ij} \) - distance from port i to port j (nautical miles)

\( E_{ij} \) - cost of entering port j by vessel k.

\( U_j \) - unloading rate at port j (quantity per day)

\( Q_j \) - size of shipment destined for port j

\( I_k \) = \begin{cases} 1 \text{ if return voyage of vessel } k \text{ is on own account} \\ 0 \text{ otherwise} \end{cases}

\( N_k \) - Upper bound on the number of unloading ports for vessel k.

**Constraints:**

**Vessel capacity:**

\[
\sum_{j \in J} Q_j Y_{jk} \leq C_k \quad \forall k \in K
\]

**Number of destination ports per vessel:**

\[
\sum_{i \in I} \sum_{j \in J} I_{ij} X_{ijk} \leq N_k \quad \forall k \in K
\]

**Every shipment is fully loaded:**

\[
\sum_{k \in K} Y_{jk} = 1 \quad \forall j \in J
\]

**Every ship leaves any port (including origin) at most once:**

\[
\sum_{j \in J} X_{ijk} = 1 \quad \forall k \in K, i \in I
\]

**A shipment is loaded only on a ship that calls at its destination port:**
All vessels start from the origin:

\[(5) \quad \gamma_{ijk} \leq \sum_{i \in \mathcal{I}} x_{ijk} \quad \forall j \in \mathcal{J}, k \in \mathcal{K}\]

Only one final destination per vessel:

\[(6) \quad \sum_{j \in \mathcal{J}} x_{ojk} = 1 \quad \forall k \in \mathcal{K}\]

No vessel accumulation in intermediate ports:

\[(7) \quad \sum_{j \in \mathcal{J}} z_{jk} \leq 1 \quad \forall k \in \mathcal{K}\]

Objective function:

The objective is to minimize the sum of the following costs:

1. Shipping costs -

   sea days:
   \[\sum_{k \in \mathcal{K}} \left( \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{J}} x_{ijk} d_{ij} \right) s_k / v_k + \]

   Unit shipping cost:
   \[\sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{J}} a_{kj} q_j y_{ik} + \]

   return trips:
   \[\sum_{k \in \mathcal{K}} \left( \sum_{j \in \mathcal{J}} z_{jk} d_{j0} \right) r_k s_k / v_k + \]
2. Port costs -

   Port entry costs:
   \[ \sum_{k \in K} \sum_{j \in J} \left( \sum_{i \in I} X_{ijk} \right) E_{jk} + \]

   cost of unloading time:
   \[ \sum_{k \in K} \left( \sum_{i \in I} Q_i Y_{ik} / U_i \right) P_k + \]

3. Demurrage (for unoccupied vessels till next period):
   \[ \sum_{k \in K} X_{ooik} D_k \]

A problem with \( S \) ships and \( P \) ports has \( SP \cdot (P+1) \) binary variables, \( SP \) continuous ones, and \( 5S + P + 3PS \) constraints, and is too big to be solved optimally, even for moderate values of \( S \) and \( P \).
Formulation 2 - Decomposable Non-Linear Program*

This formulation uses a notation similar to the former one, but the decision variables are:

\[ X_{ijkl} = \begin{cases} 
1 & \text{if vessel } k \text{ selects route } l_k \\
0 & \text{otherwise} 
\end{cases} \]

\[ t_{kl} = \begin{cases} 
1 & \text{if vessel } k \text{ takes route } l_k \\
0 & \text{otherwise} 
\end{cases} \]

\[ \gamma_{jk} \quad \text{The share of the shipment to port } j \text{ which is loaded on vessel } k \]

Where:

\[ l_k \in L_k \quad \text{The set of feasible routes of vessel } k \text{. and} \]

\[ f(l_k) \quad \text{is the cost of vessel } k \text{ taking route } l_k. \]

The constraints are:

Vessel capacity:

\[ (1) \quad \sum_{j \in J} \sum_{l \in L_k} t_{kl} X_{ijkl} \gamma_{jk} Q_j \leq C_k \quad \forall k \in K \]

* This approach was proposed by Prof. C. Mount-Campbell of the Department of Industrial and Systems Engineering, The Ohio State University.
One feasible route per vessel:

(2) \[ \sum_{l \in L_k} t_{kl} = 1 \quad \forall k \in K \]

Every shipment is fully loaded:

(3) \[ \sum_{k \in K} \sum_{l \in L_k} t_{kl} x_{jkl} y_{jk} = 1 \quad \forall j \in J \]

Enough capacity enters every port:

(4) \[ \sum_{k \in K} \sum_{l \in L_k} t_{kl} x_{jkl} c_k \geq Q_j \quad \forall j \in J \]

This last constraint assures that feasible solutions are generated.

The objective function minimizes the sum of the following costs:

Unit shipping costs:

\[ \sum_{k \in K} \sum_{j \in J} \sum_{l \in L_k} \alpha_{kj} Q_j y_{jk} t_{kl} x_{jkl} + \]

Cost of unloading time:

\[ \sum_{k \in K} \sum_{j \in J} \sum_{l \in L_k} Q_j y_{jk} t_{kl} x_{jkl} p_k / U_j + \]

Routing costs:

\[ \sum_{k \in K} \sum_{l \in L_k} t_{kl} f(l_k) \]

The route cost function of a ship, \( f(l_k) \), includes the cost of sea days, empty return leg, demurrage and port entry charges, as applicable to the specific ship and route.

This formulation allows decomposition of the problem into a binary routing problem, in \( t_{kl} \) and \( x_{jkl} \), and a
loading problem in $Y_{ik}$. For a given routing the loading problem is a generalized transportation problem.

For every ship a feasible route $l_k$ is defined by a set of $\lambda_{ik}$ which satisfies the constraint on the number of unloading ports for that ship, $N_k$.

Thus, full enumeration of the feasible routes and solution of the loading problem for each set of feasible routes will yield the optimal solution to the overall problem. A problem with $S$ ships and $P$ unloading ports has $2^{SP}$ possible routings, part of which are infeasible, and another part may be disregarded because a solution to the generalized transportation problem will have at least $P$ port entries and no more that $S+P$ of them. Thus, the loading problem must be solved only for routing combinations in this range, and the solution with the minimal cost of the objective function is the optimal one.
APPENDIX B

Optimizing Algorithm for Smaller Problems

Following is the optimizing algorithm for problems where the product of the number of ships by the number of ports is less than 25. This algorithm is based on Formula­tion 2 in Appendix A.

1. Read Data: Ships, ports, distances and shipments.
2. Check sufficient total capacity of ships, if insufficient go to 12.
3. Generate the first binary combination with the first P of the $X_{jk}$'s equal 1 and the rest zero.
4. Check sufficient capacity entering every port and the number of unloading ports per vessel. If the combination is infeasible go to 5, else go to 6.
5. Generate a new binary combination, if it has SP ones go to 11, if it has more than S+P ones go to 5, else go to 4.
6. Set the cost of the for which $X_{jk}=0$ to a high value.
7. Solve the generalized transportation problem.
8. Set $X_{jk}=0$ if $Y_{jk}=0$.
9. Calculate the shortest routes for the ships, and the solution cost.
10. Compare current solution with last min. cost solution, store if cheaper, go to 5.

11. Print min. cost solution.

12. Stop
APPENDIX C

Heuristic Scheduling Algorithm

Computer Program List
01290     DO 177 I=1,IS
01300     GACT(I,J)=0.0
01310     177 CONTINUE
01320     176 CONTINUE
01330     JI=IP+1
01340     24 CONTINUE
01350     C TAKE FARTHEST PORT LEFT
01360     JI=JI-1
01370     IF (JI.EQ.0) GO TO 40
01380     IP=INDP(JI)
01390     IF (Q1(IPORT),EQ.0.0) GO TO 24
01400     IF (ISS(EQ.0) GO TO 40
01410     DO 23 ISS=I
01420     WORK(I)=SMAP(PR5(I),IPORT)
01430     IND5(I)=PR5(I)
01440     23 CONTINUE
01450     C ***************** SORTING OF SHIPS FOR A GIVEN PORT ***
01460     CALL ORDER(WORK,ISS,INDS,1)
01470     II=1
01480     28 CONTINUE
01490     IF (II-ISS) 30,30,24
01500     30 CONTINUE
01510     ISS=INDS(I1)
01520     TOL=Q1(IPORT)*FLEX
01530     QF=Q1(IPORT)-TOL
01540     IF (CAP1(ISSIP),EQ.0.0) GO TO 20
01550     IF (USC(ISSIP),IPORT),GE.99.0) GO TO 20
01560     IF (CAP1(ISSIP)-QF) 25,26,27
01570     20 CONTINUE
01580     II=II+1
01590     GO TO 28
01600     25 CONTINUE
01610     COST=(DIST(IPORT)XI(RLEG(ISSIP))XI(S(ISSIP),/U(ISSIP)+
01620     1 CAP1(ISSIP)*P(ISSIP),/U(IPORT)+USC(ISSIP),IPORT))-
01630     2 E((ISSIP),IPORT)-DEMI(ISSIP))/CAP1(ISSIP)*DIST(IPORT)/100000.
01640     IF (COST1.0+P7)*CHM(E(ISSIP,IPORT)) 45,45,20
01650     45 CONTINUE
01660     ROUTE(I),ISSIP=IPORT
01670     Q1(IPORT)=Q1(IPORT)-CAP1(ISSIP)
01680     IF (Q1(IPORT),LT.TOL) Q1(IPORT)=0.0
01690     GACT(ISSIP),IPORT=CAP1(ISSIP)
01700     CAP1(ISSIP)=0.0
01710     II=II+1
01720     IF (II-ISS) 28,28,24
01730     26 CONTINUE
01740     COST=(DIST(IPORT)XI(RLEG(ISSIP))XI(S(ISSIP),/U(ISSIP)+
01750     1 CAP1(ISSIP)*P(ISSIP),/U(IPORT)+USC(ISSIP),IPORT))-
01760     2 E((ISSIP),IPORT)-DEMI(ISSIP))/CAP1(ISSIP)*DIST(IPORT)/100000.
01770     IF (COST1.0+P7)*CHM(E(ISSIP,IPORT)) 47,47,20
01780     47 CONTINUE
01790     ROUTE(I),ISSIP=IPORT
01800     GACT(ISSIP),IPORT=CAP1(ISSIP)
01810     Q1(IPORT)=0.0
01820     CAP1(ISSIP)=0.0
01830     GO TO 24
01840     27 CONTINUE
01850     IDK=0
01860     DO 441 KUS=1,IS
01870     IF (CAP1(KUS)0.0) IDK=IDK+1
01880     441 CONTINUE
01890     JOK=0
01900     DO 442 KUS=1,IP
01910     IF (Q1(KUS),0.0) JOK=JOK+1
01920     442 CONTINUE
IF (JOK.EQ.1) GO TO 48

QM=Q1(IPORT)+TOL
IF (CAP1(ISHIP)-QM) 31,31,29

CONTINUE

GA=MINI(CAP1(ISHIP),Q1(IPORT)+TOL)
COST=((DISO(IPORT)+(1.0+IRLEG(ISHIP))*S(ISHIP)/V(ISHIP))

1 QM*(P(ISHIP)/U/IPORT)+USC(ISHIP,IPORT))
2 EC(ISHIP,IPORT)-DEM(ISHIP)/(QAMISO(IPORT)/100000.)

IF (IS6.EQ.0) GO TO 49
IF (COST-(1.0+P7)*CMIN(IPORT)) 49,49,20

CONTINUE

ROUTE(I,ISHIP)=IPORT
QACT(ISHIP,IPORT)=GA
Q1(IPORT)=0.0
CAP1(ISHIP)=0.0
GO TO 24

CONTINUE

ROUTE(I,ISHIP)=IPORT
QACT(ISHIP,IPORT)=CAP1(ISHIP)
Q1(IPORT)=0.0
CAP1(ISHIP)=0.0
GO TO 24

CONTINUE

TCOST=999999.
DO 34 J=1,IP
IF (J.EQ.IPORT) GO TO 34
IF (Q1(J).EQ.0.0) GO TO 34
IF (USC(ISHIP,J).GE.99.0) GO TO 34

OO-CAPK(ISHIP)-OM
OMJ=Q1(J)+Q(J)+FLEX
DIST=DISO(J)+DIS(J,IPORT)+DISO(IPORT)-IRLEG(ISHIP)
ALT2=DISO(J)+DIS(J,IPORT)+DISO(IPORT)-IRLEG(ISHIP)

IF (DIST.GT.ALT2) GO TO 37
CONTINUE

DIST=ALT2
M1=J
M2=IPORT
GO TO 39

CONTINUE

DIST=ALT2
M1=J
M2=IPORT

CONTINUE

QPORT=Q1(IPORT)
QJ=MINI(CAP1(ISHIP)-Q1(IPORT),Q1(J))
SURP=CAP1(ISHIP)-Q1(IPORT)-QJ

IF (SURP) 42,42,41

CONTINUE

CARGO=CAP1(ISHIP)-SURP
QPORT=Q1(PORT)+(1.0+SURP/CARGO)

CONTINUE

IF (QPORT.GT.QM) QPORT=QM
QJ=QJ(1.0+SURP/CARGO)

CONTINUE

COST=(DIST*S(ISHIP)/V(ISHIP)+QPORT*(P(ISHIP)/U/IPORT)

1 USC(ISHIP,IPORT)+QJ*(P(ISHIP)/U/J)+USC(ISHIP,J))
2 EC(ISHIP,IPORT)+EC(ISHIP,J)-DEM(ISHIP)/(QIPORT*DISO(IPORT)+QJ*

DISO(J))/1000000.)

CONTINUE

TCOST=COST
M1=MI
M2=MQ
QPORT=QIPORT
QJ=QJ

CONTINUE

CONTINUE
DO 261 I=1,IS
IF (CAPI(I).GT.0.0) IOK=IOK+1
260 CONTINUE
JOK=0
DO 262 J=1,IP
IF (Q1(J).GT.0.0) JOK=JOK+1
264 CONTINUE
IF (JOK.EQ.2.AND.IOK.EQ.1) GO TO 44
CIMI=CHIN(MIO)
DO 784 J=1,IP
IF (INDP(J).EQ.MIO) DISH10=DISH0(J)
IF (INDP(J).EQ.M20) DISM20=DISH0(J)
CONTINUE
IF (DISM20.GT.DISM10) CIMI=CMIN(M20)
IF (TCOST.GT.1.0/(P7)*CINI) 344,344,24
CONTINUE
CONTINUE
ROUTE(1,ISHIP)=M10
ROUTE(2,ISHIP)=M20
CAPI(ISHIP)=0.0
Q1(IPORT)=0.0
IF (M10.EQ.IPORT) GO TO 46
500 QACT(ISHIP,IPORT)=QPORT0
QACT(ISHIP,M10)=QJO
Q1(H10)=Q1(M10)=QJO
IF (Q1(M10).LT.TL.0.0) Q1(M10)=0.0
TOL=Q1(M10)*FLEX
IF (Q1(M10).LT.TOL) Q1(M10)=0.0
GO TO 24
2870 CONTINUE
2880 QACT(ISHIP,IPORT)=QPORT0
QACT(ISHIP,M20)=QJO
Q1(M20)=Q1(M20)=QJO
IF (Q1(M20).LT.TL.0.0) Q1(M20)=0.0
TOL=Q1(M20)*FLEX
IF (Q1(M20).LT.TOL) Q1(M20)=0.0
GO TO 24
2940 CONTINUE
40 CONTINUE
2950 C
J1=IP+1
2980 124 CONTINUE
C TAKE THE FARDEST PORT
J1=J1-1
3010 IF (J1.EQ.0) GO TO 140
3020 IPORT=INDP(J1)
3030 IF (Q1(IPORT).EQ.0.0) GO TO 124
3040 IF (ISA.EQ.0.0) GO TO 140
3050 DO 123 I=1,IS6
3060 WORK(I)=SHEF(PR6(I),IPORT)
3070 IND5(I)=PR6(I)
3080 123 CONTINUE
3090 CALL ORDER(WORK,IS6,IND5,I1)
3100 I1=1
3110 128 CONTINUE
3110 IF (I1-IS6) 130,130,124
3130 130 CONTINUE
ISHIP=INDS(I1)
3140 TOL=Q(IPORT)*FLEX
3150 IF (Q(IPORT).GT.QF) 125,126,127
3160 IF (CAPI(ISHIP).EQ.0.0) GO TO 120
3180 IF (USC(ISHIP,IPORT).GE.99.0) GO TO 120
3190 IF (CAPI(ISHIP).GT.0.0) 125,126,127
120 CONTINUE
I1 = I1 + 1
GO TO 128
CONTINUE

03240  125  ROUTE(1,ISHIP)=IPORT
03250  Q1(IPORT) = Q1(IPORT) - CAP1(ISHIP)
03260  IF (Q1(IPORT) .LT. TOL) Q1(IPORT) = 0.0
03270  OACT(ISHIP,IPORT) = CAP1(ISHIP)
03280  CAP1(ISHIP) = 0.0
03290  I1 = I1 + 1
03300  IF (I1 .LE. I56) 128, 128, 124
CONTINUE

03310  ROUTE(1,ISHIP)=IPORT
03320  OACT(ISHIP,IPORT) = CAP1(ISHIP)
03330  Q1(IPORT) = 0.0
03340  GO TO 124
CONTINUE

03350  127  ROUTE(1,ISHIP)=IPORT
03360  OACT(ISHIP,IPORT) = OA
03370  O1(IPORT) = 0.0
03380  CAPl(ISHIP) = 0.0
GO TO 124
CONTINUE

03390  QM = Q1(IPORT) + TOL
03400  IF (CAPl(ISHIP) .LT. QM) 131, 131, 129
CONTINUE

03410  CONTINUE
03420  J = MIN1(CAPl(ISHIP), Q1(IPORT) + TOL)
03430  ROUTE(1,ISHIP)=IPORT
03440  OACT(ISHIP,IPORT) = QA
03450  Q1(IPORT) = 0.0
03460  CAPl(ISHIP) = 0.0
03470  GO TO 124
CONTINUE

03480  131  ROUTE(1,ISHIP)=IPORT
03490  OACT(ISHIP,IPORT) = CAPl(ISHIP)
03500  Q1(IPORT) = 0.0
03510  CAPl(ISHIP) = 0.0
03520  GO TO 124
CONTINUE

03530  COST2 = 999999
DO 134 J = 1, IPORT
03550  IF (J = IPORT) GO TO 134
03560  IF (Q1(J) .EQ. 0.0) GO TO 134
03570  IF (USC(ISHIP, J) .GE. 99.0) GO TO 134
03590  TOL2 = Q(J) * FLEX
03600  DIST = DISO(IPORT) + DIS(IPORT, J) + DISO(J) * IRLEG(ISHIP)
03620  ALT2 = DISO(J) + DIS(J, IPORT) + DISO(IPORT) * IRLEG(ISHIP)
03630  M1 = IPORT
03640  H2 = J
03650  IF (DIST .LT. ALT2) GO TO 137
CONTINUE

03660  DIST = ALT2
03670  CONTINUE
03680  H1 = J
03690  H2 = IPORT
03700  CONTINUE

03710  137  QIPORT = Q1(IPORT)
03720  J = MIN1(CAPl(ISHIP) - Q1(IPORT) - Q1(J))
03730  SURP = CAPl(ISHIP) - Q1(IPORT) - QJ
03740  IF (SURP) 142, 142, 141
CONTINUE

03750  141  CONTINUE
03760  IF (SURP .LT. TOL - TOL2) 145, 145, 147
CONTINUE

03770  145  CONTINUE
03780  CARGo = CAPl(IPORT) - SURP
03790  QIPORT = QIPORT + (1.0 + SURP/CARGO)
03810  QJ = QJ + (1.0 + SURP/CARGO)
03820  GO TO 142
CONTINUE

03830  147  CONTINUE
03840  QIPORT = QIPORT + TOL
03850  Q=QJ+TOL2
03860  CONTINUE
03870  COST=COST+$S(ISHIP)/U(ISHIP)+QIMPORT*($P(ISHIP)/U(IIMPORT)
03880  1+USC(ISSHIP,IIMPORT)+QJ*(P(ISHIP)/U(J)+USC(ISSHIP,J)) +
03890  2*EC(ISSHIP,IIMPORT)+EC(ISSHIP,J)-DEM(ISSHIP)/{(QIMPORT*DISO(IIMPORT)
03900  3*QJ*DISO(J))/1000000.}
03910  IF (COST-COST2) 143,134,134
03920  CONTINUE
03930  COST2=COST
03940  M10=M1
03950  M20=M2
03960  QPORTO=QIMPORT
03970  QJ=QJ
03980  CONTINUE
03990  IF (CAP1(ISSHIP)-QPORTO-QJ0) 144,144,150
04000  CONTINUE
04010  ROUTE(1,ISSHIP)=M10
04020  ROUTE(2,ISSHIP)=M20
04030  CAP1(IIMPORT)=0.0
04040  Q1(IIMPORT)=0.0
04050  IF (M10.EQ.IIMPORT) GO TO 146
04060  GACT(ISSHIP,IIMPORT)=QPORTO
04070  GACT(ISSHIP,M10)=QJ0
04080  Q1(M10)=Q1(M10)-QJ0
04090  V1QV=Q1(M10),LT,0.0) Q1(M10)=0.0
04100  TOL=Q(M10)#FLEX
04110  IF (Q(M10),LE,TOL) Q1(M10)=0.0
04120  GO TO 124
04130  CONTINUE
04140  GACT(ISSHIP,IIMPORT)=QPORTO
04150  GACT(ISSHIP,M20)=QJ0
04160  Q1(M20)=Q1(M10)-QJ0
04170  IF (Q1(M20),LT,0.0) Q1(M20)=0.0
04180  TOL=Q(M20)#FLEX
04190  IF (Q1(M20),LE,TOL) Q1(M20)=0.0
04200  GO TO 124
04210  CONTINUE
04220  IF (J1.EQ.2) GO TO 144
04225  COST3=999999
04230  DO 151 J1=1,IP
04240  IF (Q1(J1),LE,0.0) GO TO 151
04250  IF (J1.EQ.IIMPORT) GO TO 151
04260  IF (USC(ISSHIP,J1),GE,99.0) GO TO 151
04270  DO 152 K1=1,IP
04280  IF (K1.EQ.IIMPORT) GO TO 152
04290  IF (K1.EQ.J1) GO TO 152
04300  IF (Q1(K1),LE,0.0) GO TO 152
04310  IF (USC(ISSHIP,K1),GE,99.0) GO TO 152
04320  QNI=Q1(K1)+Q1(IIMPORT)#FLEX
04330  QM1=Q1(J1)+Q1(J1)#FLEX
04340  QM2=Q1(K1)+Q1(K1)#FLEX
04350  QNI=Q1(IIMPORT)+Q1(J1)#FLEX
04360  QFJ=Q1(J1)-Q1(K1)#FLEX
04370  QFJ=Q1(K1)-Q1(K1)#FLEX
04380  QFJ=Q1(K1)-Q1(K1)#FLEX
04390  IF (CAP1(ISSHIP)-QNI-QMK) 151,151,153
04400  CONTINUE
04410  IF (CAP1(ISSHIP)-QNI-QMK) 152,152,154
04420  CONTINUE
04430  ALT(1)=DISO(IIMPORT)+DISO(J1)+DIS(J1)+DIS(J1)#IRLEG(ISSHIP)
04440  ALT(2)=DISO(IIMPORT)+DISO(K1)+DIS(J1)+DIS(J1)#IRLEG(ISSHIP)
04450  ALT(3)=DISO(J1)+DIS(J1)+DIS(J1)+DIS(J1)#IRLEG(ISSHIP)
04460  ALT(4)=DISO(J1)+DIS(J1)+DIS(J1)+DIS(J1)#IRLEG(ISSHIP)
04470  ALT(5)=DISO(K1)+DIS(J1)+DIS(J1)+DIS(J1)#IRLEG(ISSHIP)
04480  ALT(6)=DISO(K1)+DIS(J1)+DIS(J1)+DIS(J1)#IRLEG(ISSHIP)
05130 4 QK=DISO(K)/1000000.
05140 IF (COST-COST3) 169,152,152
05150 CONTINUE
05160 COST3=COST
05170 Q10=Q1
05180 QJ3=QJ
05190 QKO=QK
05200 M13=M1
05210 M23=M2
05220 M33=M3
05230 J0=J
05240 KO=K
05250 152 CONTINUE
05260 151 CONTINUE
05270 IF (COST2-COST3) 144,144,170
05280 CONTINUE
05290 ROUTE(1,ISHIP)=M13
05300 ROUTE(2,ISHIP)=M23
05310 ROUTE(3,ISHIP)=M33
05320 CAP1(ISHIP)=0.0
05330 Q1(IPORT)=0.0
05340 QACT(ISHIP,IPORT)=Q10
05350 QACT(ISHIP,J0)=QJ3
05360 QACT(ISHIP,K0)=QKO
05370 Q1(J0)=Q1(J0)-QJ3
05380 IF (Q1(J0).LT.0.0) Q1(J0)=0.0
05390 TOL=Q(J0).FLEX
05400 IF (Q1(J0).LT.TOL) Q1(J0)=0.0
05410 Q1(K0)=Q1(K0)-QKO
05420 IF (Q1(K0).LT.0.0) Q1(K0)=0.0
05430 TOL=Q(K0).FLEX
05440 IF (Q1(K0).LT.TOL) Q1(K0)=0.0
05450 GO TO 124
05460 140 CONTINUE
05470 DO 171 J=1,IP
05480 IF (Q1(J).GT.0.0) GO TO 172
05490 171 CONTINUE
05500 GO TO 174
05510 172 CONTINUE
05520 DO 173 I=1,IS
05530 IF (CAP1(I).GT.0.0) GO TO 180
05540 173 CONTINUE
05550 P7=P70+0.12
05560 P70=P7
05570 WRITE (6,998) P7
05580 IF (P7.GT.5.0) GO TO 90
05590 GO TO 275
05600 180 CONTINUE
05610 LUK=0
05620 DO 302 I=1,IS
05630 IF (CAP1(I).GT.0.0) GO TO 304
05640 GO TO 302
05650 304 CONTINUE
05660 LUK=0
05670 DO 306 J=1,IP
05680 IF (USC(I,J).GT.99.0.AND.Q1(J).GT.0.0) LUK=LUK+1
05690 306 CONTINUE
05700 IF (LUK) 302,302,310
05710 310 CONTINUE
05720 LUK=1
05730 DO 308 J=1,IP
05740 SMF(I,J)=SMF(I,J)/(LUK+1.0)
05750 308 CONTINUE
05760 302 CONTINUE.
06410  DO 221 I=1,IS  
06420  DO 222 J=1,IP  
06430  QACTO(I,J)=QACT(I,J)  
06440  222 CONTINUE  
06450  DO 223 K=1,4.  
06460  ROUTEK(I,K)=ROUTE(K,I)  
06470  223 CONTINUE  
06480  221 CONTINUE  
06490  DIF=(CO-CMTM)/CMTM  
06500  IF (DIF-0.005) 240,240,290  
06510  290 CONTINUE  
06520  P7=P70  
06530  P7=P7-0.05  
06540  P7=P7  
06550  WRITE*(6,998)P7  
06560  GO TO 275  
06570  240 CONTINUE  
06580  IF (ITER-5) 241,90,90  
06590  241 CONTINUE  
06600  P7=P70  
06610  P7=P7+0.15  
06620  P7=P7  
06630  GO TO 275  
06640  90 CONTINUE  
06650  DO 80 I=1,IS  
06660  WRITE*(6,908)(QACT0(I,J),J=1,IP)  
06670  908 FORMAT(/,5X,15F8.0)  
06680  80 CONTINUE  
06690  WRITE*(6,899)TCOST,CO  
06700  899 FORMAT(/,8X,'SCHEDULE COST :',F10.0,  
06710  1 //15X,'COST PER MIL, TON-MILES :',F8.1)  
06720  STOP  
06730  END  
06740  SUBROUTINE ORDER(A,K,IND,L)  
06750  DIMENSION A(K),IND(K)  
06760  IF (L.EQ.1) GO TO 30  
06770  DO 11 I=1,K  
06780  IND(I)=I  
06790  11 CONTINUE  
06800  30 CONTINUE  
06810  C SORT A  
06820  K1=K-1  
06830  K2=K1  
06840  DO 23 J=1,K1  
06850  IN=0  
06860  DO 22 I=1,K2  
06870  IF (A(I).GT.A(I+1)) GO TO 20  
06880  20 CONTINUE  
06890  IN=1  
06900  AB=A(I)  
06910  A(I)=A(I+1)  
06920  A(I+1)=AB  
06930  IJ=IND(I)  
06940  IND(I)=IND(I+1)  
06950  IND(I+1)=IJ  
06960  22 CONTINUE  
06970  IF (IN.EQ.0) GO TO 24  
06980  K2=K2-1  
06990  23 CONTINUE  
07000  24 CONTINUE  
07010  RETURN  
07020  END
APPENDIX D

Required Number of Random Schedules

Suppose all the possible schedules for a given problem are arranged according to their cost, from the cheapest to the most expensive one. Then, \(1-P\) is the probability that a random schedule will not be in the cheapest \(100\cdot P\%\) of the schedules.

The probability that \(n\) random schedules will not be in that range is \((1-P)^n\). The probability that at least one schedule out of \(n\) will be in that range is \(1 - (1-P)^n\). By specifying the required confidence the value of \(n\), the required number of schedules, can be calculated.

**Example:** It is required that at 99\% confidence at least one schedule will be at the lowest 0.1\% of the schedules:

\[
1 - (1 - .001)^n = .99
\]

\[
n = \log 0.01/\log .999
\]

\[
n = -2/-0.000435 = 4,598.
\]
APPENDIX E

Elements of Data Base

Following is the list of ships with their costs which were used in the analysis, and a list of the ports on which the analysis was based.
Table 15: List of ships and their employment term (all costs in dollars)

<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>Day</th>
<th>Port</th>
<th>Cost per ton shipped to port No.</th>
<th>Cost per port day</th>
<th>Cost per day</th>
<th>Cost per week</th>
<th>Cost per month</th>
<th>Cost per quarter</th>
<th>Cost per year</th>
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<td>July</td>
<td>12</td>
<td>11968</td>
<td>6295</td>
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<td>153290</td>
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</tr>
</tbody>
</table>

**Notes:**
- Data compiled from R. Perry (Shipping Consultant) Ltd., Shipping Statistics and Economics.
- Data from various sources, including:
  1. Atlantic Venture
  2. London Banker
  3. Martin
  4. Nutham
  5. Atlantic Luger
  6. Atlantic Venture
  7. London Banker
  8. Martin
  9. Golden Tinty
  10. Doncaster
  11. GoldenStar
  12. Macarone
  13. Morris
  14. Augustus
  15. Atlantic Venture
  16. London Banker
  17. Martin
  18. Golden Tinty
  19. Doncaster
  20. GoldenStar

**Comments:**
- Columns include:
  1. Name of ship
  2. Year
  3. Day
  4. Port
  5. Cost per ton shipped to port
  6. Cost per port day
  7. Cost per day
  8. Cost per week
  9. Cost per month
  10. Cost per quarter
  11. Cost per year
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GLOSSARY OF TERMS*

BAREBOAT CHARTER (BBC). The charterer receives a "bare ship" and he is looking after its manning, maintenance and supplies at his own expense.

BULK CARRIER. A ship designed to carry dry cargo in bulk, sometimes equipped with its own unloading gear.

CHARTER PARTY. A contract between a shipowner and an operator in which the operator receives a vessel for his use under specified terms.

CONTRACT OF AFFREIGHTMENT. A contract in which a carrier undertakes to carry specified quantities between certain ports within a specified time frame at a certain freight rate. The shipper is obligated to ship those quantities by the carrier.

COST, INSURANCE, FREIGHT (CIF). The cost CIF of goods includes all costs of the good up to the specified destination, including freight and insurance.

DEADWEIGHT (DWT). The carrying capacity of a vessel, including cargo, bunkers, water and all other supplies and materials, expressed in tons.

DEMURRAGE. Compensation for extra delay beyond the agreed time paid to the shipowner in case a vessel does not complete loading and/or discharge within the time allowed in the contract.

FREE ON BOARD (FOB). The cost FOB of goods includes all costs of the good, until it is loaded on board of a vessel at the specified port. It does not include the sea freight or insurance.

GROSS REGISTERED TONNAGE (GRT). The volume of the enclosed spaces of the vessel in hundreds cubic feet.

LINER SERVICE. A scheduled service of vessels between specified ports, available to all shippers.

SISTER SHIP. Another ship built according to the same plans.

SUBLET. A sub-charter of the chartered vessel to another party.

TANKER. A vessel designed for carriage of liquid cargoes in bulk.

TIME CHARTER. The charterer hires the vessel for a stated period.

VOYAGE CHARTER. Under a voyage charter shipowners undertake to put a vessel at charterers' disposal for the carriage of cargo from certain ports to destination ports in a certain zone.
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Books


Articles


Other Publications


Drewry, H. P. (Shipping Consultants) Ltd. Shipping Statistics and Economics, Jan.-June, 1979


