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STUDIES ON THE FUTURE OF ATLANTIC PORTS

by

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THE FUTURE OF ATLANTIC PORTS

A Review of the Status and Analysis of Characteristics

by

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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SEA GRANT PROGRAM

Administrative Statement

The studies on The Future of Atlantic Ports is the first of a two part sequal. This first study reviews the past and present capabilities of U.S. Atlantic coast ports and projects the extent to which the ports will successfully meet future requirements.

This study effort, I believe, satisfies an urgent need for a comprehensive understanding of the numerous factors that influence the success of ocean transportation. The significant aspects include:

- A world review of the demand and supply of shipping;
- An estimation of commodity flows, advances in ocean technology and development of a standard of measurement of port capacity to assist in projecting future needs;
- The development of multiport models to analyze competitive effects among ports serving the same region; and
- Suggestions for change in the physical form and use of U.S. Atlantic ports to meet future demands.

Funds to carry out this research came in part from the NOAA Office of Sea Grant, U.S. Department of Commerce, on Grants Nos. GH-88 and 2-35150 (1970-1972), from the International Ford Foundation and from the Massachusetts Institute of Technology.

Ira Dyer
Director

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The project research and editorial effort were also supported by the Massachusetts Institute of Technology and the International Ford Foundation.

The author acknowledges the contributions of Professor J. Devanney III, M.I.T., Professor A. Novaes of the University of Sao Paulo, Brazil, as well as those of Morten Ringard, Larry Hill, Ronald Parsons and L. H. Tan.

The authors also wish to thank the many persons who typed, proofread and helped in various ways with this report.

Abstract

This study is an attempt to review the capacity of ports on the U. S. Atlantic Coast, the past, present and projected future demand imposed upon them and their resulting ability to meet their future requirements.

The changing functions of ports are discussed as they affect port operations themselves as well as the port interface with various modes of transportation. The facilities in the subject ports are analyzed including their past and current use, and an attempt made to derive a measure of port capacity. The increasing competition among ports for the same hinterland which has resulted in the growing concept of the regional port. To analyze the competitive effects among ports serving the same region or regional parts multiport models were developed. The use and structure of multipurpose ports and multiport models is discussed, with particular reference to the analysis of the U. S. Atlantic seaboard. Future needs are estimated by projecting demand and forecasting type and form of commodity movements as well as trends in Transportation Technology. The report concludes with the requirements for change in the physical form and use of U. S. Atlantic Ports to meet such future demands.

This report is the first of a two part sequel. The second report develops and presents the methodology for multipurpose port and multiport analysis, and planning, and will be published in 1973.

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1.0 INTRODUCTION

The rapid changes in the technological environment of marine transportation and the increasing integration of waterborne, air and land transport systems have fostered a revolution in the design and operation of vehicles, material handling, terminal facilities, unitization and storage which is resulting in major changes in port function and use. Also affected are operational methods and commodity flow patterns. These changes are dynamic and will continue to influence transportation systems design, construction and operation.

This revolution has been accompanied by concurrent upheaval in the traditional role of the seaport, and has fostered a new set of concepts governing the design and location of port facilities which more realistically reflects the function of ocean transportation as being but one subsystem of a complex intermodal transportation and distribution system.

Within this context most existing commercial port facilities are already obsolescent, without a chance of recuperating operational effectiveness unless changes reflecting future requirements are implemented without delay. The economic consequences of decaying port systems usually affects a large segment of economic and commercial activity of a region. As ports continue to atrophy the resulting increases in foreign and domestic trade costs of bulk and break bulk commodities will be reflected in the posture, standard of living, employment level and economic growth of the region.

At this time it is critical that an examination and assessment of port requirements be made in terms of both present and projected demands, evolving technology in transportation and port systems, labor and social demands, investment availability, and potential alternate use of port facilities and resources.

This study focuses on the evaluation of seaport requirements for the Atlantic seaboard of the United States. In it we analyze their capacity in the light of evolving technology and the feasibility of future port development, against the general background of continued economic and technological progress. Among the background considerations were:

- An examination of new concepts and their effect on the technological environment of ocean transportation and port development.

- The development of forecasts of commodity flow shipping activity and the attendant demands on port facilities and transportation system requirements on the Atlantic seaboard of the U.S.A.

- Preparation of an inventory and description of existing port facilities on the Atlantic seaboard of the U.S.A.

- An evaluation of the potential of existing ports as the location of new major seaport developments or the development of completely new port facilities, or terminals.

- Analysis and assessment of the assembled data leading to recommendations for future port development.

- Development of a preliminary plan for seaport development which will serve as a basic guide for future decisions.

- Development of a multiport multipurpose simulation model to provide the tools for analyzing different port uses and developments.

- Methodology for optimizing investment and operational decisions of a total seaboard port systems basis.

The healthy economic development of waterfront and coastal areas depends largely on the effective availability of transportation resources and interfaces. Access to the open sea as well as to inland or coastal road, rail and waterways is becoming of increasing importance and a large factor negating the advantages of ports in densely populated urban areas. Already today, severe bottlenecks exist at focal points along these transportation routes in many parts of the U.S.A.

In addition, the vast increase in ship investment, ship operating, port handling, cargo handling, and warehousing costs are increasingly making conventional port locations and operations obsolete. These considerations have led to the development of new port facilities in many parts of the world, which are removed from historic port sites and urban concentrations. Many of these facilities are replacing older ports as a result of their improved operational and cost effectiveness.

Aside from the consideration of developing major seaports, alternative approaches to developments which can meet future demand requirements for an effective intermodal transportation system should be investigated. While limited water depths may not permit economic development of oil or dry bulk ports for transocean trade in some areas, there are many obvious advantages in integrating coastal bulk movements by more extensive coastal barge or ship systems.

Another consideration is the ability to instigate more effective work rules and resulting use and cost of labor when applied to newly activated or developing technology, which an established port cannot do easily.

Major changes have occurred in transportation technology in recent years and a large amount of research is currently under way devoted to the development of new vehicles, terminal operations, information and cargo control and handling equipment, etc. Some of these developments have had a long lead time and their potential application to maritime transportation can, therefore, be forecast with a fair amount of reliability. While some of these concepts require intensive engineering effort alone to achieve a feasible vehicle design, others require developments, particularly subsystem development, in related areas such as propulsion, thrusters, or material handling equipment. Most of the recent developments have been in cargo handling systems and have resulted in changes in transportation vehicle design configuration. The increased popularity of container and unitized cargo handling is forecast to continue and may reach a level of about 70-80% of all dry, general cargo serving the U.S. East Coast trade. While fairly good forecasts can be made on the potential growth of transportation requirements, technological forecasting techniques, such as the Delphi method,* have been successfully used to derive statistical estimates of the

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*The Delphi method is a scientific forecasting tool which has proven to be extremely useful in developing projections of technological advances. The method involves interrogation of a controlled group of experts, the analysis of their responses, and a feedback process which minimizes uncertainty in the final forecasts. The Delphi method is described more fully in Appendix A.

trend and sensitivity of technical developments for time periods extending over 30 years or more. Recent work in total transportation system design has resulted in the establishment of basic development aims and requirements. These in turn have given impetus to research and development projects with a larger degree of direction. On the other hand, we note that a large discrepancy continues to exist between the progress made in the development of requirements and the physical or operational implementation of recommended solutions.

Whether or not a developed technology will be adapted for commercial applications is more a function of need than the fact of development.* It is for this reason that the forecasts for the next 20-year period were prepared based on the current data base as influenced by extrapolation analysis and consider the following factors:

a. Demand assessment analysis results and cargo flow corrected, where applicable, for the effect of future technological developments and resulting economic and operational factors on the demand or cargo flow.

b. Significance and effect on systems of the interaction among selected prime parameters affecting performance of ocean shipping vehicles.

c. Interaction with other technical areas and intensity of effort in these areas.

d. Effect of private and public investment involvement.

e. Effect of political and military contingencies.

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*J. Schmookler, Invention and Economic Growth (Cambridge, Harvard University Press, 1966).

f. Effect of national laws such as those pertaining to safety, pollution (oily ballast, sewage, etc.), and radiation.

g. Effect of proprietary labor, social, management and administrative factors.

Based upon the forecasts of the technological environment in shipping and port development and the forecast of port demands and facility requirements, a general assessment of seaport needs was projected for the time periods of 1975, 1980 and 1990. The assessment considers the economic and social effect of four courses of action: (a) develop major seaports, (b) develop specialized seaport(s), (c) modernize existing facilities, and (d) develop no additional port facilities but effectively maintain existing ports with limited investment.

In response to these projected needs, alternative seaport concepts have evolved during the development of forecast of technological environment and port demands. These were based on the following criteria:

a. Physical characteristics (wharf area, land area, water depth, channel width, etc.) of the site.

b. Intermodal transportation links.

c. Costs of construction, operations, and indirect support (cost of improving rail, road and air transportation, etc.)

d. Economic effects upon the seaport, seaport area, Atlantic seaboard and its hinterland.

e. Social effects upon the seaport, seaport area, Atlantic seaboard and its hinterland.

f. Ecological effects.

g. Legal and labor aspects.

h. Anticipated problems and constraints.

Based on U.S. East Coast seaport needs and the evaluation of seaport sites, the feasibility and economic justification for the development of new seaports was determined. If such development was deemed feasible, the factors affecting the planning were enumerated, and a general plan was formulated for such seaport development to match projected growing needs.

2.0 PORT FUNCTIONS

The function of a port is basically to transfer cargo between inland feeder and coastal transportation and oceangoing ships. Subordinate functions include interfeeder transfer, cargo consolidation and cargo storage. Although these functions have not changed, the methods used in their performance have been radically modified in recent years. The overriding factors influencing changed methods and procedures are ship and feeder turnaround, resulting from the higher capital intensity of ship and feeder systems. The unit investment and operating costs of ships and vehicles have increased dramatically, with the resulting demand to minimize port time. Changes in port methods and procedures are largely affected by port facilities, port technology, port labor, port management, and the customs of the port. The last factor usually influences the way in which work is performed and controlled and has probably a larger influence on the effectiveness of use of labor and physical resources than any other.

Port technology and configuration have in the past been largely affected by the demand of multipurpose port capability. As a result, most traditional ports were able to handle the transfer and/or storage of many commodities, yet none very effectively. Flexibility of operations and diversity of use of resources used to be a major criteria of port design, investment and management. The major change in ship and feeder technology has resulted in a large dislocation of port resource use. This, in turn, contributed to major imbalance in the use of facilities and resources. Similarly, the conventional assumptions of port capacity and throughput were challenged by the interfacing transportation modes.

A major aspect is the relation of the port towards hinterland or service areas. While traditional ports were designed to serve a larger urban area surrounding the port, modern ports are called upon to serve a much wider hinterland of which one or more urban concentrations form a part. As a result, most new port developments are established in nonurban locations with prime emphasis on water and inland accessibility from a transport point of view. These developments have also resulted in a reevaluation of the advantages of multipurpose versus specialized ports. With the increasing specialization in handling and transfer techniques of both bulk and general cargoes and the resulting requirements for massive investments in specialized handling and storage equipment, specialized ports and port facilities are on the increase. This factor is also emphasized by the different access and ship handling needs introduced by specialized ships and inland feeders being served by modern ports. Specialized ports are usually developed around specialized terminals and berths whose approaches and accesses are designed to effectively support certain types of ships and feeder vehicles. Typical examples are liquid and dry bulk terminals with mechanized or pipeline inland feeder connections, container terminals, or ports specializing in quick ship turnaround and inland feeder turnaround capability and the provision of extensive parking lot type marshalling capability. These considerations are similarly influenced by the advantage of functional integration and operational separation of activities which, in turn, assure controlled circulation and movement in the port or terminal. This, in turn, assures effective use and utilization of equipment, facilities, manpower, and available land area.

Port labor is traditionally casual labor. Similarly, the responsibility for the use of port labor has for many years been spread over a large number of operators and agencies. Modern port developments require centralized control and assignment of port labor which, in turn, usually results in de-casualization. In this regard, some of the recent negotiations have guaranteed work hours or guaranteed annual income by port labor, which are just one of many manifestations of the expected trend.

A modern port also requires a different approach to management. In many instances where centralized port management of all port factors was difficult or unfeasible, an increasing number of operators have opted to purchase or lease major terminal facilities or berths to assure integrated control and management of all important factors required to perform the port functions.

These trends are expected to continue to grow as the number and capacity of specialized ocean carriers increases. As indicated in Figure 1 the percentage of specialized carrier capacity among the world merchant fleets has more than doubled in the past decade and can be expected to level if it is close to 80% of total capacity by 1980. This, in turn, will make the multipurpose port or berth largely obsolete as an increasing percentage of cargoes is handled through specialized facilities. It can easily be shown that the future demand for multipurpose port or berth facilities is rapidly diminishing. This fact above all should influence the investment and use planning of ports on the Atlantic seaboard of the U.S.A.

A port is an operational system in which methods of operations research are effectively applied for decision-making. Basically, in structuring a port model or analysis, port operations are broken down into constituent parts and then expressed in mathematical notation in such a way that the capacity of the port or its component parts can be related to the cost of its provision or operation. The effects on costs and ship inland transport and cargo time are obviously also important parameters. These and other factors contribute to port productivity, effectiveness and quality of service.

For the purposes of this study port cargo functions are divided into the broad categories of:

General Dry Cargo
Containerized and/or Unitized Cargo
Liquid Bulk Cargo
Dry Bulk Cargo

There obviously are other cargo handling types (such as rolling cargo) and handling types could be broken down into more detail. Yet these four categories usually suffice, as the general terminal characteristics implied cover basically all major types of cargo transfer.

The objectives of a port are generally to perform the demanded cargo transfer functions at least cost and at maximum ratio consistent with the intermittancy and technological requirements of the land and water vehicles whose interface the port provides. In practice the objectives and resulting functions of a port may be skewed by particular conditions such as the effects of rate structures, customs and inspections, discounting of bills of lading or afreightments, and various trading policies which may result in widening the port function and changing the port objectives. The port may then have to include such additional functions as warehousing, cargo consolidation/ deconsolidation, cargo distribution, packaging, and others. The functions of a port are often influenced by local conditions and practices both from within and without the port. These conditions may be imposed by physical layout, facilities, environmental, economic, political, labor and other factors all of which complicate the establishment of a meaningful and realistic criteria.

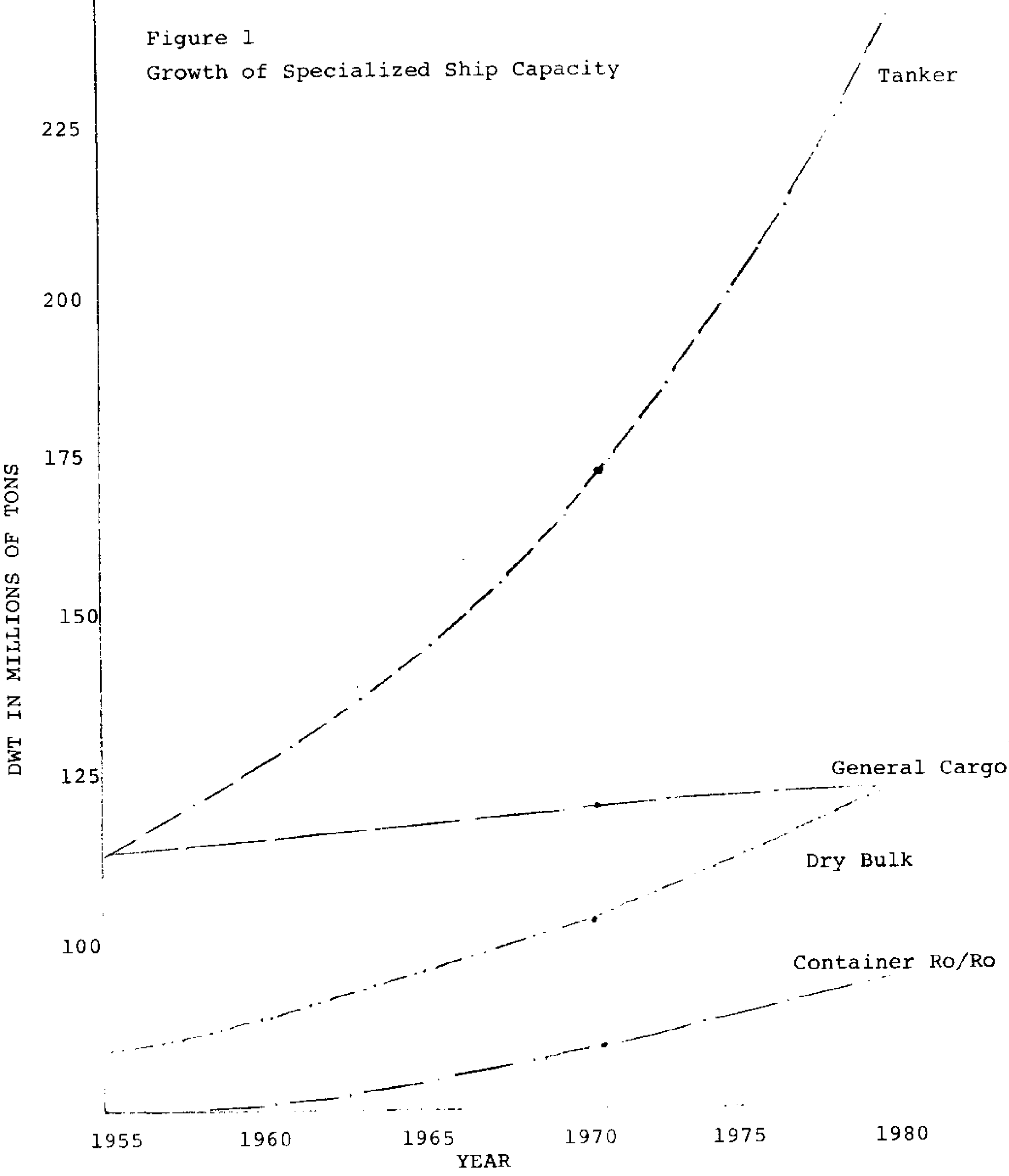
Considering the analysis of U. S. Atlantic ports, we must include all the factors imposed by the environment. The demand is imposed by commodity generation which generates a flow and a service demand for transportation from inland points of commodity generation to overseas point of commodity receipt. This is refined by route and/or port distribution demand. To fill this generated or postulated demand we select among inland feeder, port, ocean transportation and foreign port alternatives which constitute the supply as shown in Figure 2. The level of demand may be affected by total transport impedance expressed by transport cost, time and level of service. Similarly, supply capacity or availability will be affected by total transport cost, time and level of service. As a result, a "Demand-Supply Analysis" can theoretically be performed. Such analysis requires consideration of the port as an interfacing link in the transport supply chain in which inland feeder and ocean transportation is represented by the network of all alternative routes, modes, and quality of service while alternative ports are represented by their capacities for handling the model interface and other service factors. The alternative route and mode selection may be affected by a desired port distribution which determines preferred port use. Total transport impedance is the sum of all transport and transfer costs including the cost of quality of service factors such as transit time, etc.

Considering port analysis in this context, port function may be defined by a control volume into which enter inland feeder and ocean transport vehicles for the purpose of transfer of commodities which constitute the demand on the port (Figure 3). The port supplies a capacity for handling such transport vehicles and for transfer of cargo between such vehicles including intermediate storage. Because of the vast differences in unit vehicle size and, therefore, great differences in the interarrival times and queue characteristics between inland feeder and ocean transport vehicles, vehicle marshalling and commodity storage capacity form an important measure of port capacity.

The port impedance can be considered an integrated congestion cost. As capacity in terms of throughput is increased, these costs go up. While this is generally true for a static situation in which port expansion is not considered and increased capacity is supplied by increasing congestion until a limit is reached when supply becomes asymtotic the more usual case will include incremental investment which will result in a stepwise increase in port supply capacity with port impedance as shown as in Figure 4.

The manifold functions of a port can usually be divided into primary and secondary functions as listed in Tables 1 and 2, where primary functions are defined as those essential for the performance of ship, cargo and inland transport handling, while secondary functions refer to auxiliary needs that must be met in a port operation. It will be noted that many functions impose conflicting demands on the operations of a port and as a result complicate the establishment of a realistic criteria of performance.

Similarly cargo classification could be broken down into additional details such as kind, form type, feature, dimension, and density. For the purposes of this study cargo breakdown by major cargo type, and port function by major operations will be used.



References: 1) Fearnley and Egers Chartering Co., Ltd., "World Bulk Fleet," (1971-1972 monthly)
2) U. S. Maritime Administration, "Merchant Fleets of the World," (1969-1970)
3) Fairplay Publications

Fig. 2 Demand-Supply Equilibrium Analysis

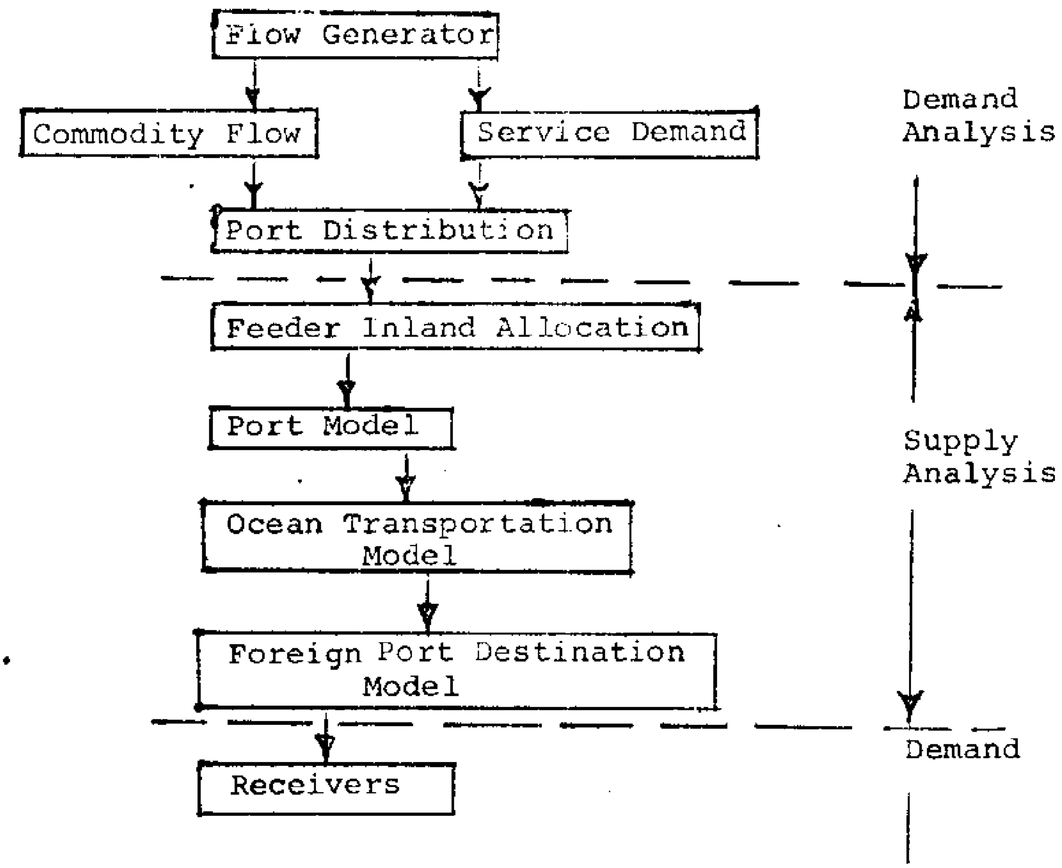


Fig. 3 Port Control Volume

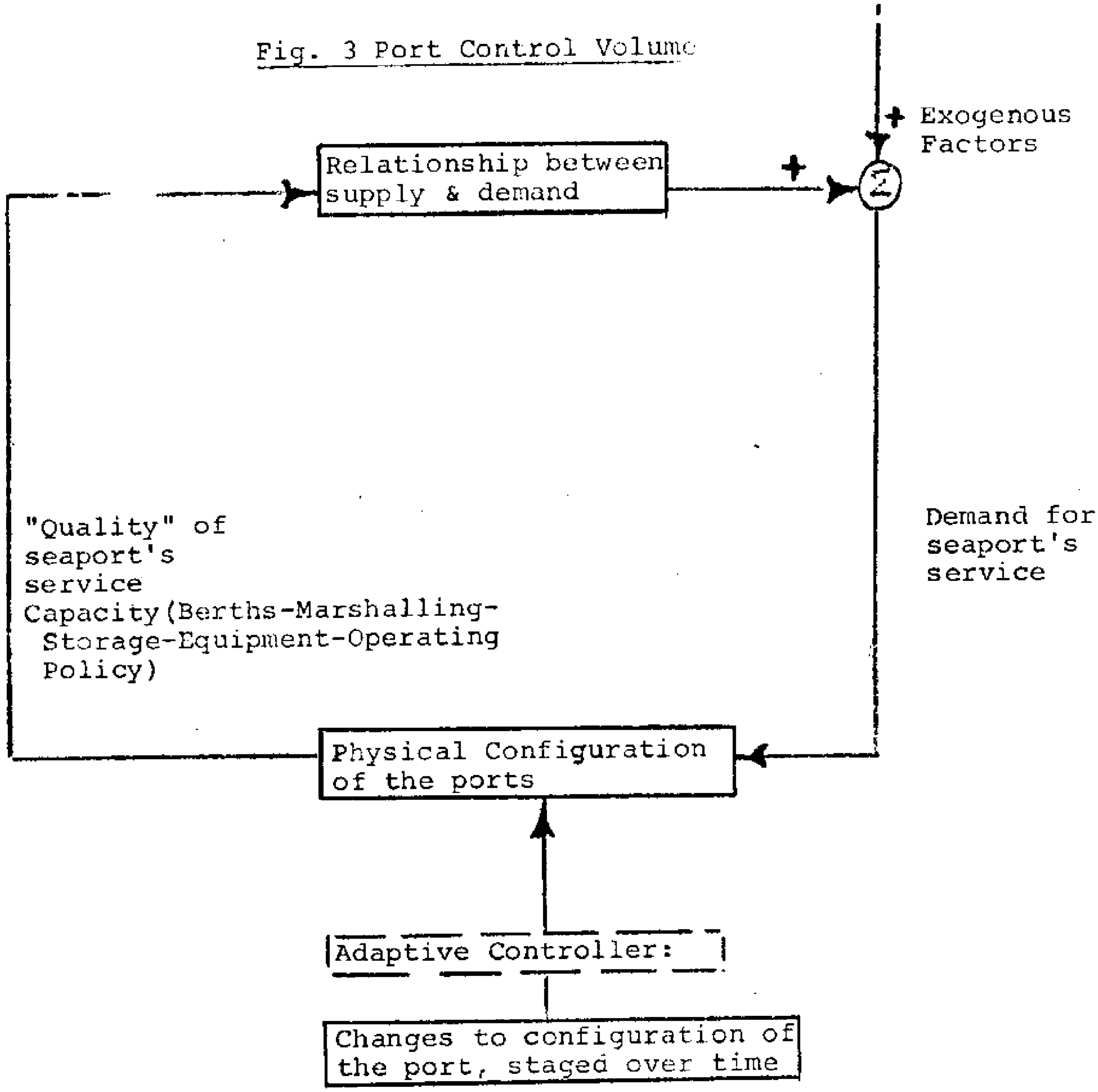


Figure 4 Demand-Supply Equilibrium

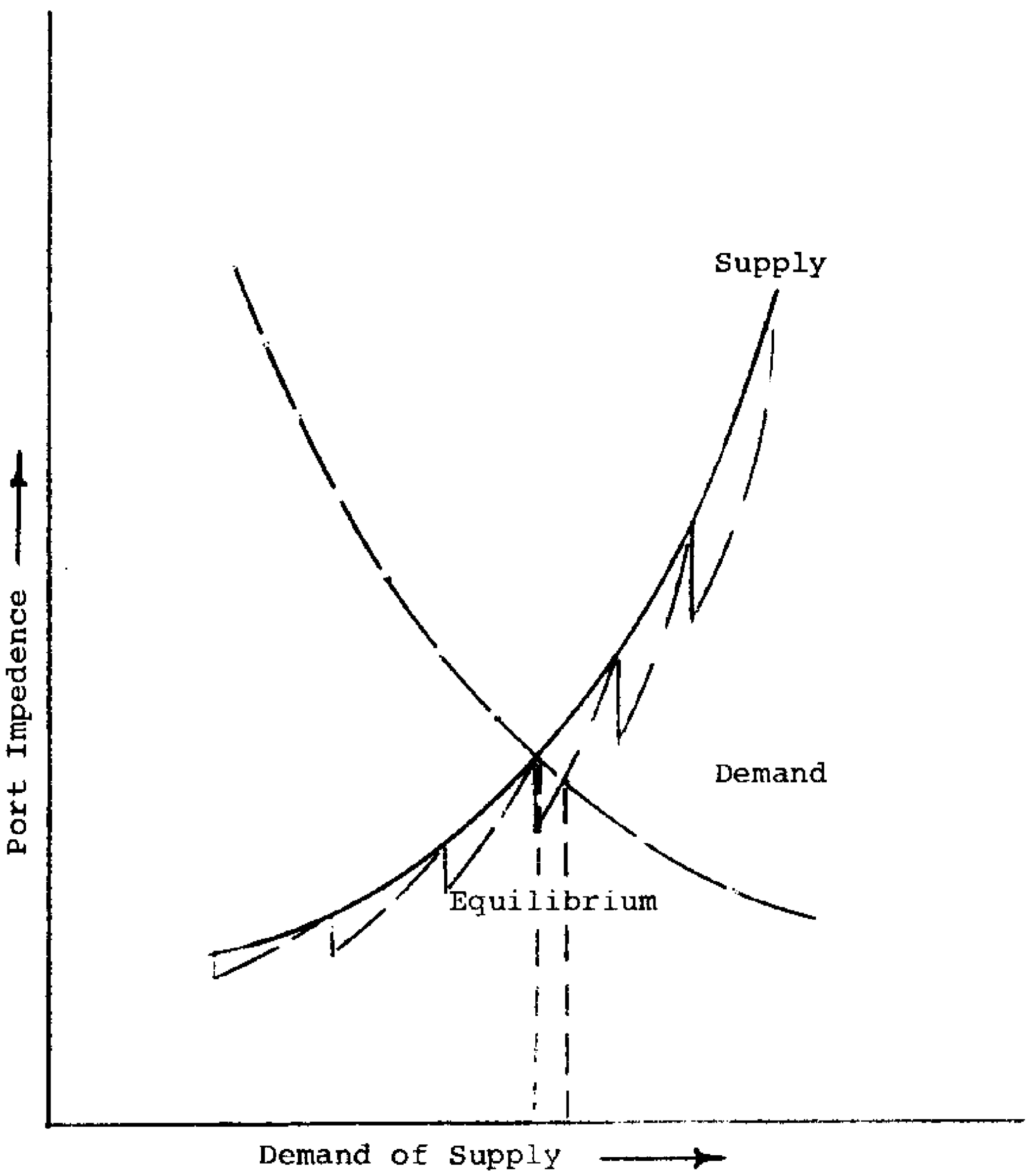


TABLE 1

PORT PRIMARY FUNCTION

Function	Operations	Facilities	Equipment/Manpower
Ship Approach & Docking	Signaling	Signal System (Painted Signal Lights, Sound Radio Radar)	Operators
	Anchorage	"Calm Waters" Anchorage Area	
	Pilotage	Pilot Base	P. Boats, Pilots
	Towing	Towboat Base	Towboats, Operators
	Mooring	Buoys, Berths	Operators
		Channels	(Dredgers)
		Break Waters Reactment Mounds	
		Locks	
Cargo Transfer Ship-Shore		Aprons (Berth)	
			Barges Lighters
			Gantry Cranes Ships Gear Trucks (land) Conveyer Belts Pipes/Pumps Grabs Forklift Trucks Quay Cranes Mobile Cranes Floating Cranes Heavy Load Trailers Straddle Carriers
			Gangs
Special Cargo Treatment	Repacking		
	Customs		
			Cranes
			Trucks
			Gangs
		Handling Area	
		Sheds	
			Hand Trucks

(continued)

Table 1 (Continued)

Store		Storage Area Open	
		Sheds	
		Aprons	
		Silos	
		Tanks	
			Conveyer Belts
			Straddle Carriers
			Trucks, Forklifts
			Tractor Trailers
		Reefer Storage	
		Cold Storage	
		Bonded Storage	
Cargo Transfer		Aprons	Locomotive
		Ramps	Trucks
			Cars
		Highway Connection	Barges
		Railyards	Cranes
		Berth	Forklift Trucks
		Siding	Conveyer Belts
		Truck Marshalling	Pipes
			Grabs
Inland Modal Approaches	Signaling	Signaling System	Operator
		Queuing Area	
		Roads	
		Railways	
		Channels	

TABLE 2

PORT SECONDARY FUNCTIONS

Operations	Facilities	Equipment/ Manpower
Ship Support (Logistics: Food, Bunker, Water, etc.)	Spec. Berth Bunker Tanks Water Connections	Cranes
Ship Maintenance	Spec. Berth Dock	
Fire Protection	Fire Station	Fire Cranes Fire Boats
Dredging		Dredgers
Pilferage Guard	Theft Alarms	
Harbor Maintenance		

3.0 FACILITIES OF U.S. PORTS ON THE ATLANTIC SEABOARD

3.1 General Remarks

In this section we summarize the statistics concerning the main characteristics for berths and storage facilities in the following nine harbors:

1. New York
2. Baltimore
3. Jacksonville
4. Portland
5. Boston
6. Providence
7. New Haven
8. Delaware River (Philadelphia, Camden, and Wilmington)
9. Hampton Roads

The statistics set forward are based on the current port reports from the Corps of Engineers, U.S. Army, and the Hampton Roads Port Annual of 1971.

The report lists a total of 2075 wharfs* for the nine ports mentioned, of which 601 (34%) are directly handling oceangoing vessels in loading and unloading commodities and passengers. It is these 601 wharfs that are treated here. The statistics then do not include idle wharfs (wharfs serving

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*Wharfs are, in this report, defined as docks handled as administrational units of the Port Authorities. Wharfs may be either finger piers or marginals; i.e., no. of finger piers + no. of marginals = no. of wharfs.

the vessels indirectly through barges) or wharfs handling refuse, seafood, excursion boats or mooring Navy vessels tugs, fireboats, ships for repair, etc.

The 601 wharfs considered represent a total berth space of approximately 658,000 feet.

The statistics are arranged with respect to the individual ports and the following purposes:

1. Handling general cargo
2. " only containerized cargo
3. " fruit
4. " grain
5. " sugar
6. " paper
7. " lumber
8. " copper
9. " gypsum rock
10. " cement
11. " coal
12. " miscellaneous dry bulk
13. " chemicals
14. " oil and petroleum products

3.2 Berth Space and Number of Wharfs

Table 3 shows how the 601 considered wharfs and the attached berth spaces are distributed between the nine harbors.

Tables 3 through 21 give the number of wharfs and the berth space for the different purposes at each individual port. In Tables 4 - 21 the data is somewhat condensed as wharfs handling "grain, sugar, paper, lumber, copper, gypsum rock, cement, coal, and miscellaneous dry bulk" are classified as "Dry Bulk." The fruit wharfs are taken into the "General Cargo" group, and "Liquid Bulk" is the same as "oil handling."

Table 22 displays the total wharf-number and berth space devoted to each purpose collectively by the ports (see Figures 16 and 17).

In Tables 22 through 35 are the wharf numbers and berth space contribution from each port to the different purposes listed.

Tables 3 and 4 are presented in Figures 5 and 6 and 16 and 17 as histograms. The berth space formation in Tables 4 through 21 is given as histograms in Figures 7 through 15.

3.3 Railway Connections

The percentages of the wharfs that have railway connections are listed in Table 37.

Three ports have special wharfs with slips for transfer of railcars from carfloats as follows:

	No. of Wharfs	No. of Slips
New York	24	56
Baltimore	7	9
Delaware River	4	5

3.4 Storage Capacities

Table 38 gives the transit shed and open storage areas for the general cargo wharfs, grain silos at the grain wharfs and the tank capacities for oil and petroleum products in the nine harbors.

The general storage capacities open to the public (not attached to special wharfs) are listed in Table 39.

3.5 Depth and Length Distributions

Tables 40 and 41 give the length-distribution for berth space units* above 300 feet for wharfs with depths greater than 20 feet.

Tables 43 and 44 present the depth-distribution for berth space units above 300 feet for wharfs with depths greater than 20 feet.

The length and depth distributions by purpose (Tables 41 and 43) are condensed to aggregate purpose grouping in Tables 42 and 45. The cumulative percentage distributions in these tables are given as histograms in Figures 19 and 21.

The cumulative percentage distributions for length and depth by port in Tables 40 and 43 are displayed in Figures 18 and 20. However, only data for ports of more than 50

---

* A berth space unit is defined as a single continuous straight length for berthing ships. A finger pier usually has three berth space units (the face and the two sides) and a marginal has one berth space unit. Both types of wharf may, however, have more units if the front is stepped or the depth is stepped.

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The depth and length distributions are handled separately since there appears to be no correlation between depth and length. (A typical example of the combined length/depth distributions is given in Table 48 for general cargo berths in New York.)

3.6 Distributions for Transit Sheds and Oil Tank Capacities

The number of transit sheds of a certain size as a function of wharf length is given in Table 46 for general cargo docks. Similarly, the tank capacities at oil docks are given as a function of the wharf length in Table 47.

The entries are very scattered. However, for the transit shed areas, some conclusion may be drawn about the maximum size to expect.

In the tables, the "characteristic length" of the wharfs is the greatest berth space unit for the particular wharfs considered.

Considering the space units by berth for general cargo wharfs in New York, the total berth capacity was derived as shown in Table 48.

Figure 5

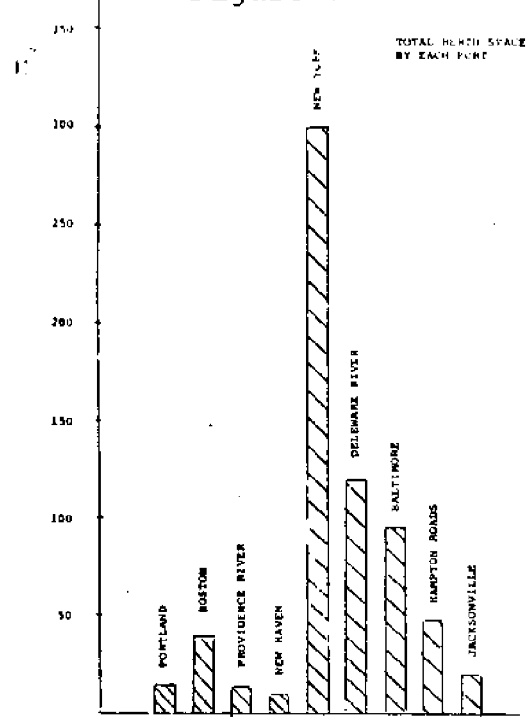


Figure 6

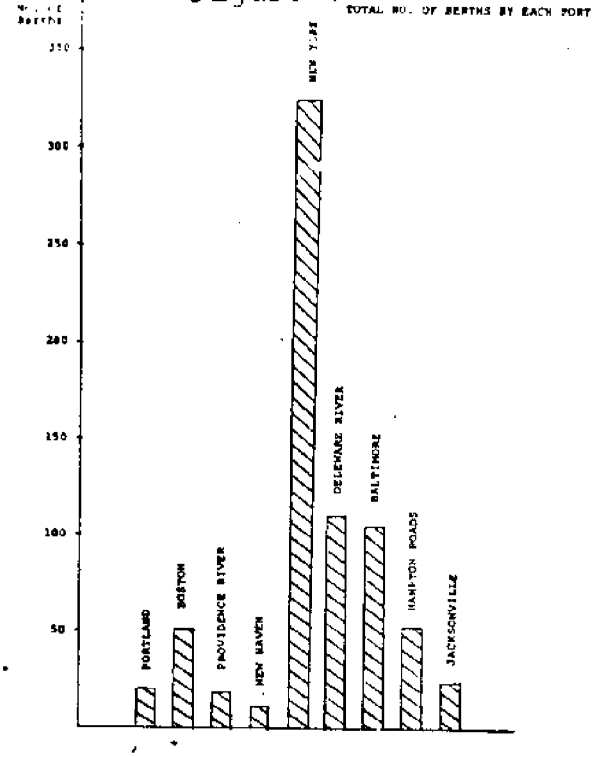


Figure 7

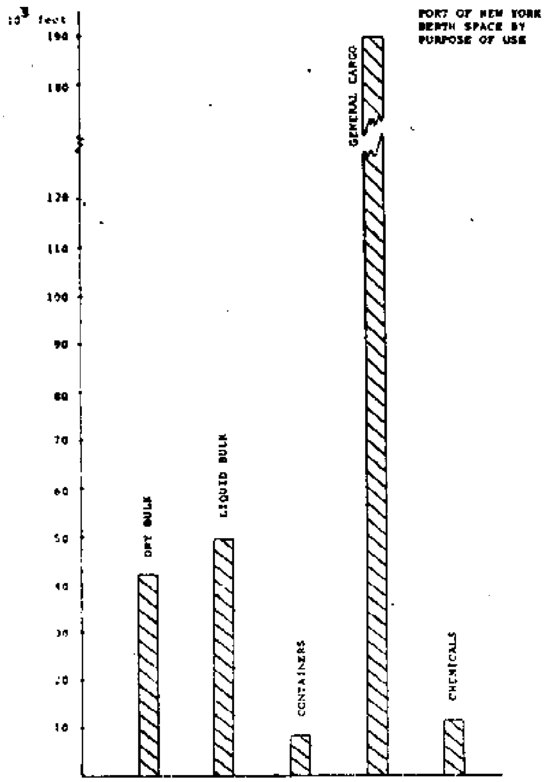


Figure 8

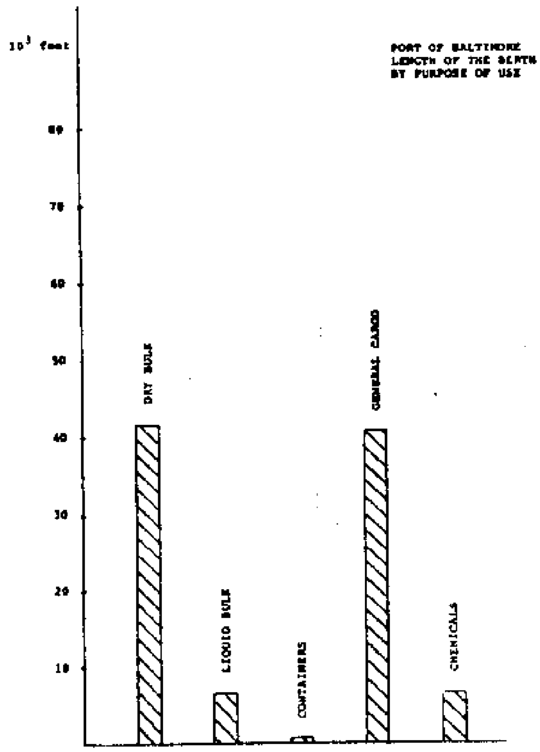


Figure 9

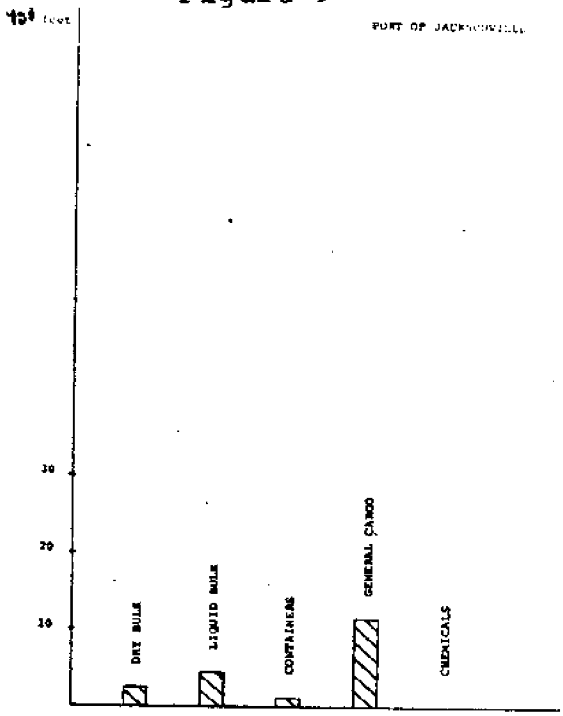


Figure 10

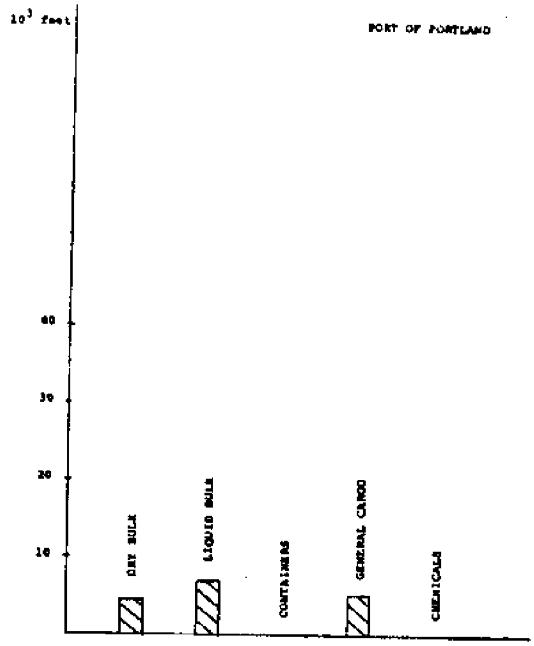


Figure 11

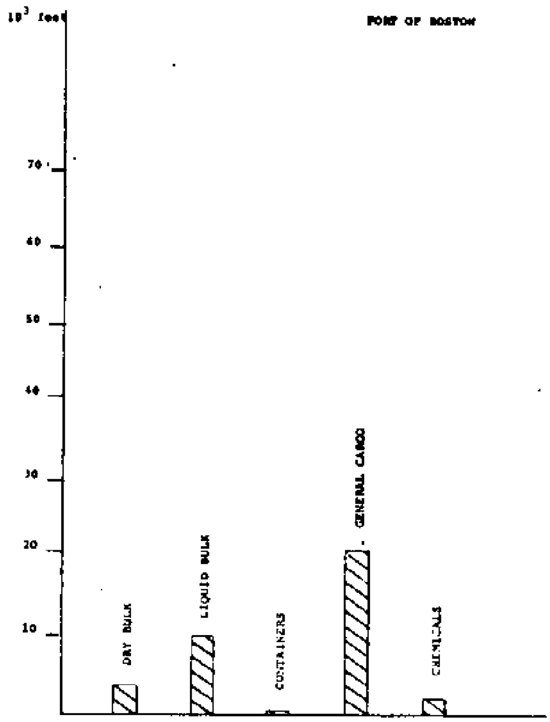
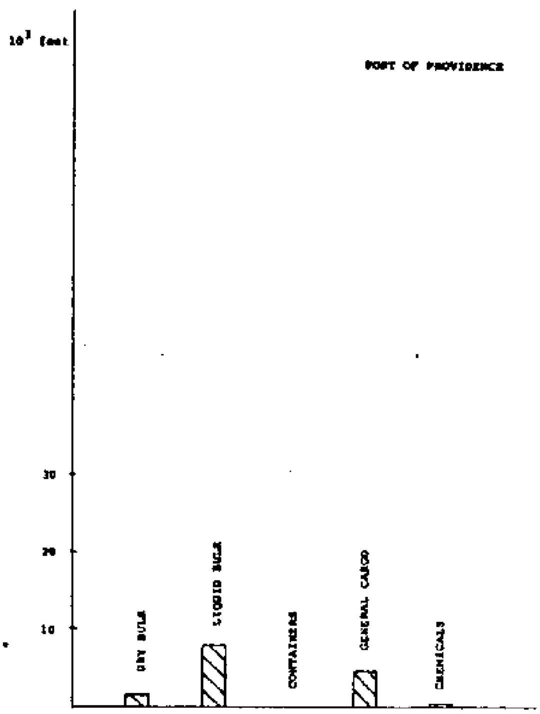


Figure 12



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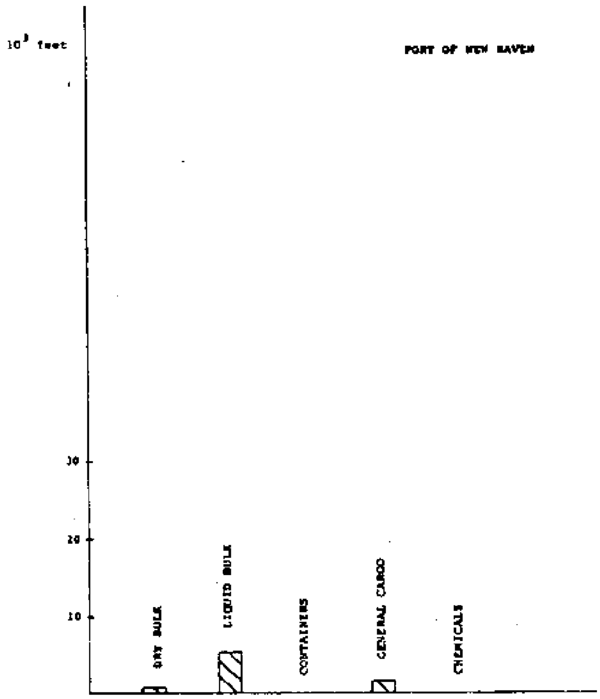


Figure 14

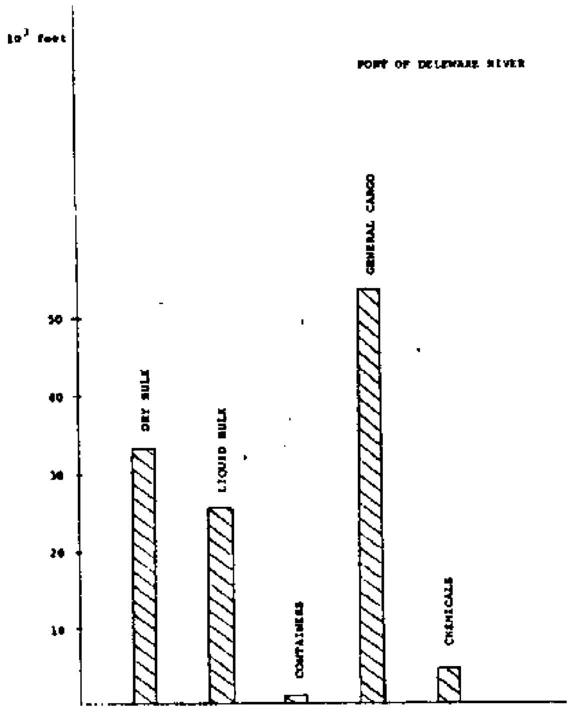


Figure 15

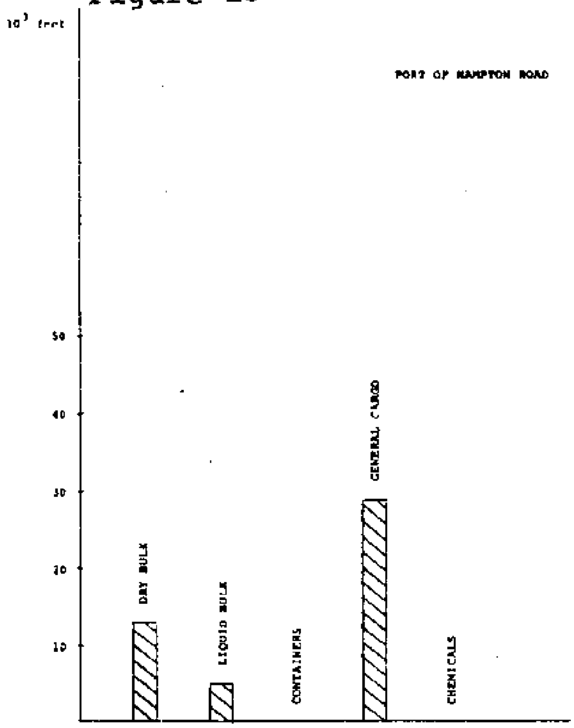
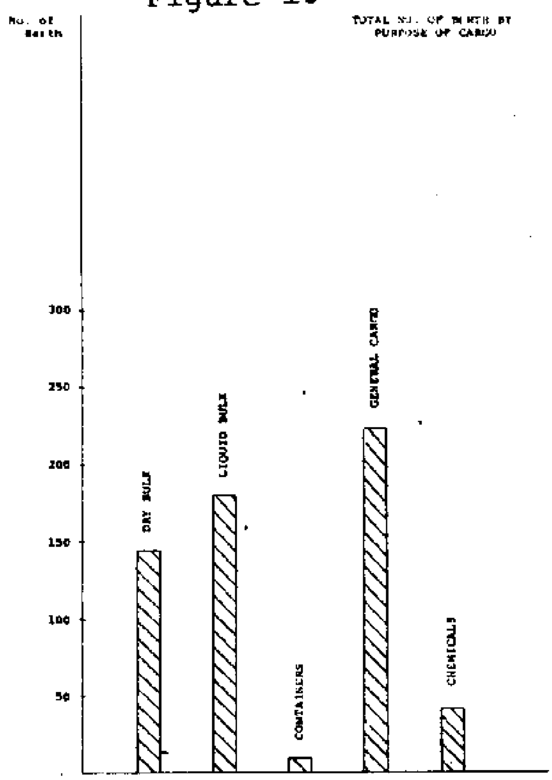


Figure 16



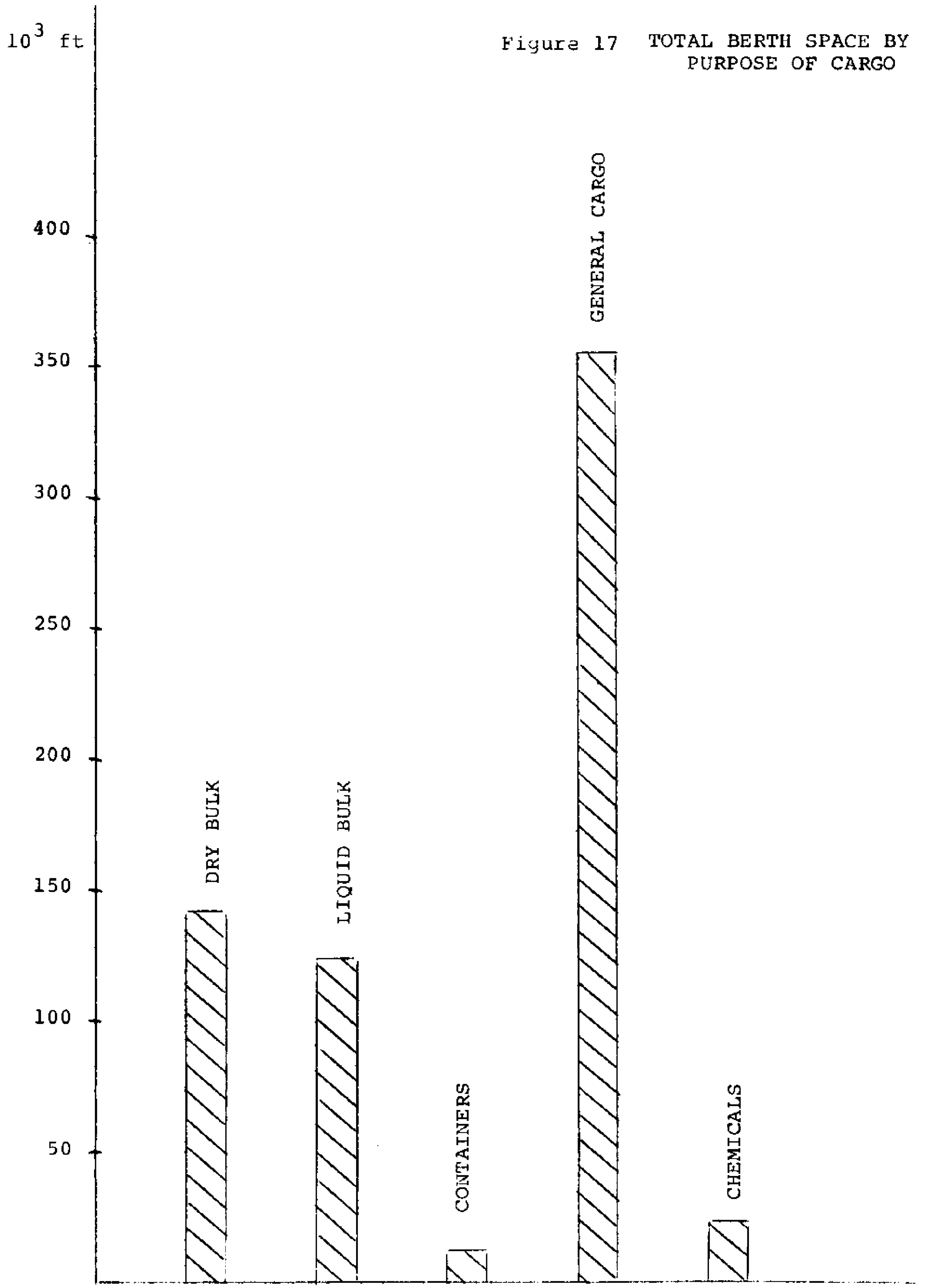


Figure 17 TOTAL BERTH SPACE BY PURPOSE OF CARGO
10^3 ft
400
350
300
250
200
150
100
50
DRY BULK
LIQUID BULK
CONTAINERS
GENERAL CARGO
CHEMICALS

Figure 18

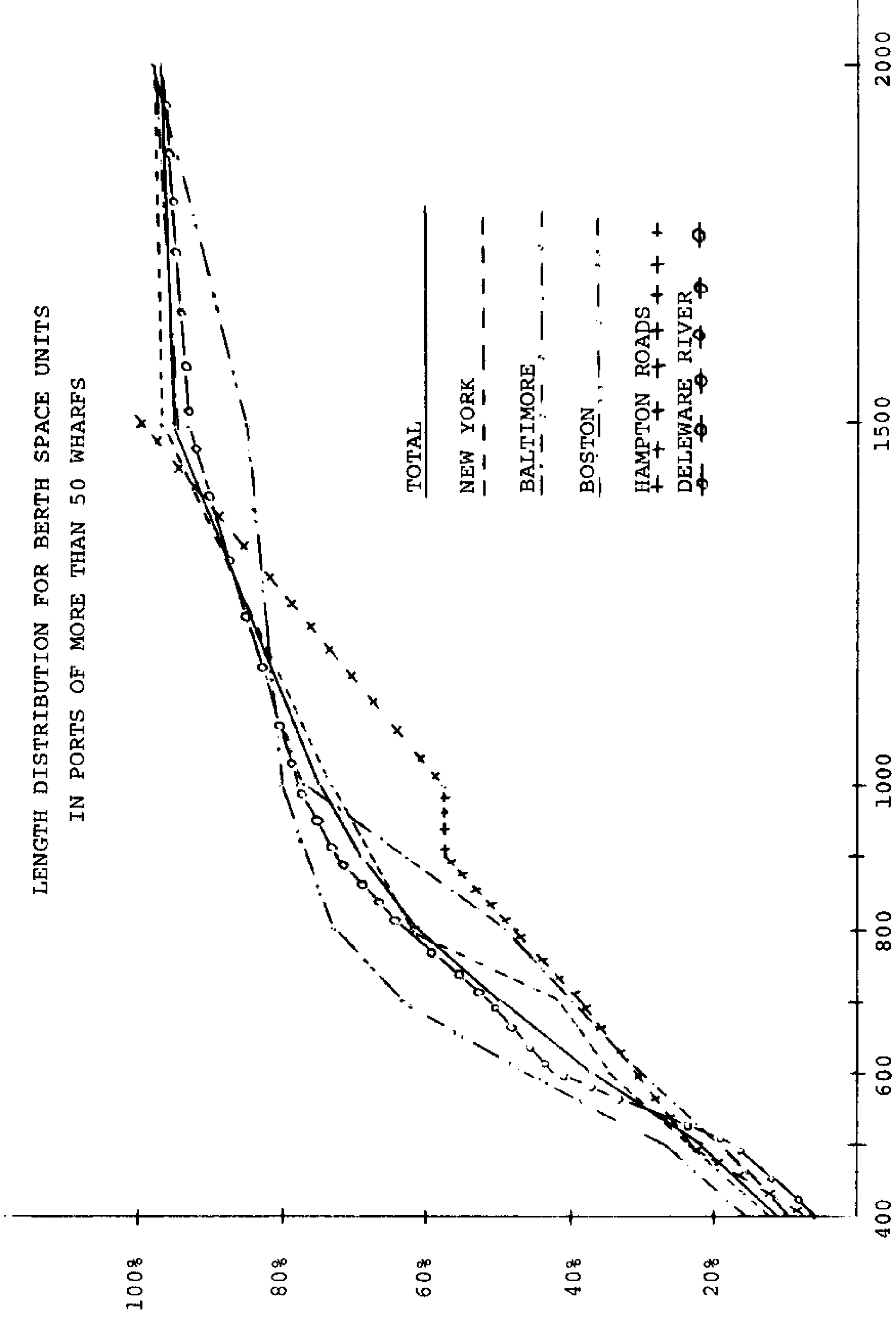

LENGTH DISTRIBUTION FOR BERTH SPACE UNITS
IN PORTS OF MORE THAN 50 WHARFS
TOTAL
NEW YORK
BALTIMORE
BOSTON
HAMPTON ROADS
DELEWARE RIVER
100%
80%
60%
40%
20%
400
600
800
1000
1500
2000

Figure 19

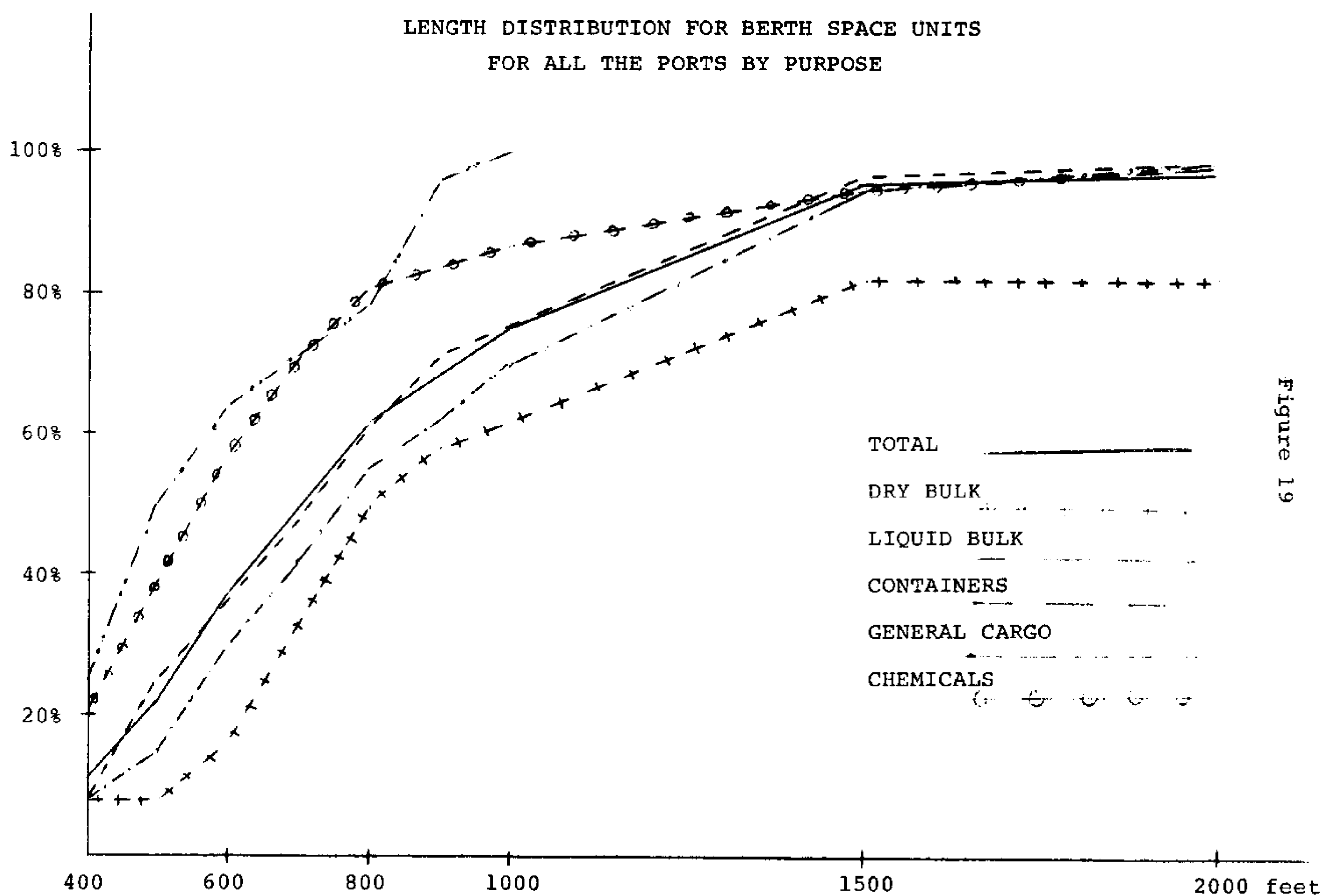

LENGTH DISTRIBUTION FOR BERTH SPACE UNITS
FOR ALL THE PORTS BY PURPOSE
100%
80%
60%
40%
20%
400
600
800
1000
1500
2000 feet
TOTAL
DRY BULK
LIQUID BULK
CONTAINERS
GENERAL CARGO
CHEMICALS

Figure 20

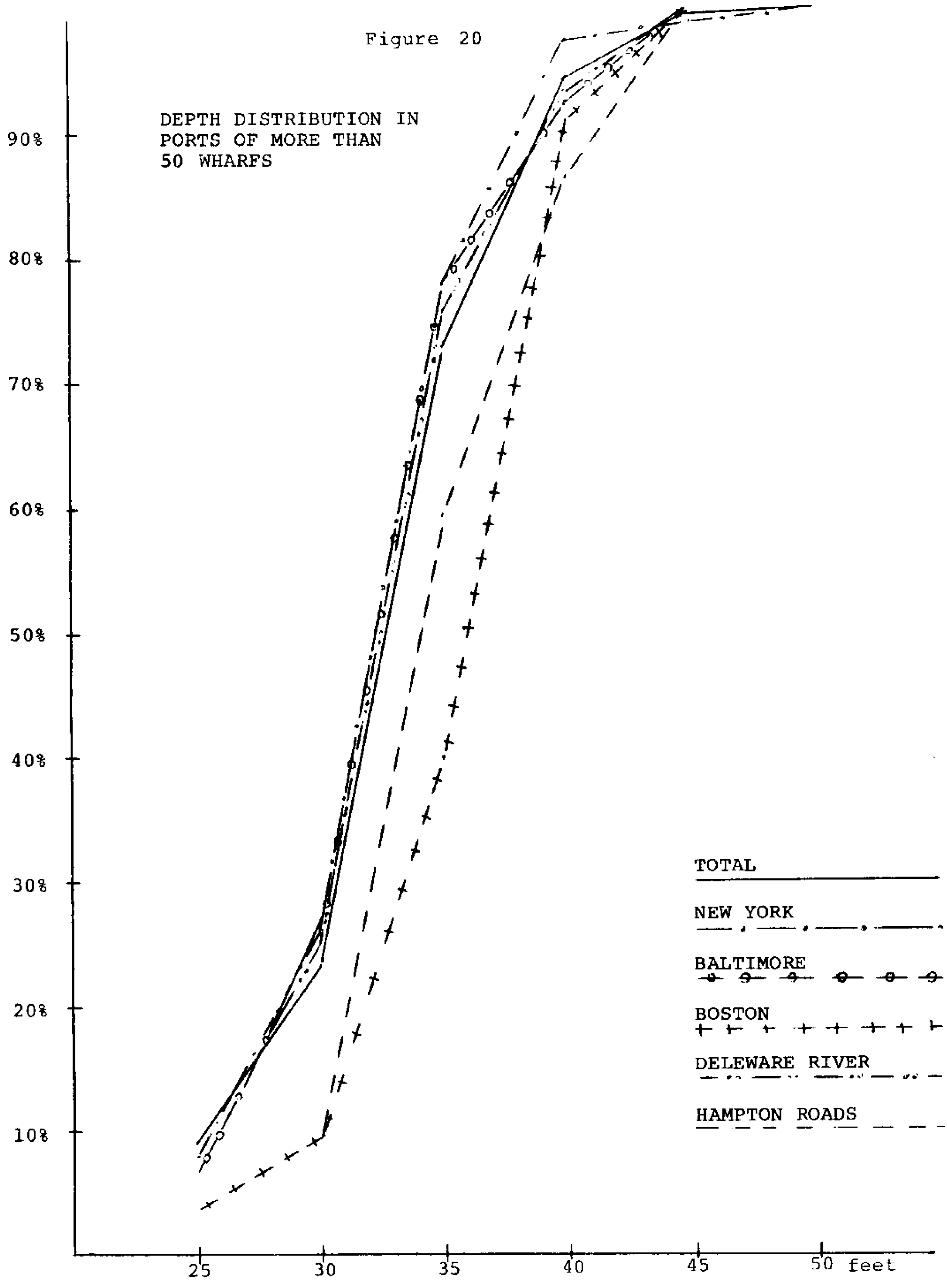

DEPTH DISTRIBUTION IN
PORTS OF MORE THAN
50 WHARFS
90%
80%
70%
60%
50%
40%
30%
20%
10%
25
30
35
40
45
50 feet
TOTAL
NEW YORK
BALTIMORE
BOSTON
DELEWARE RIVER
HAMPTON ROADS

Figure 21

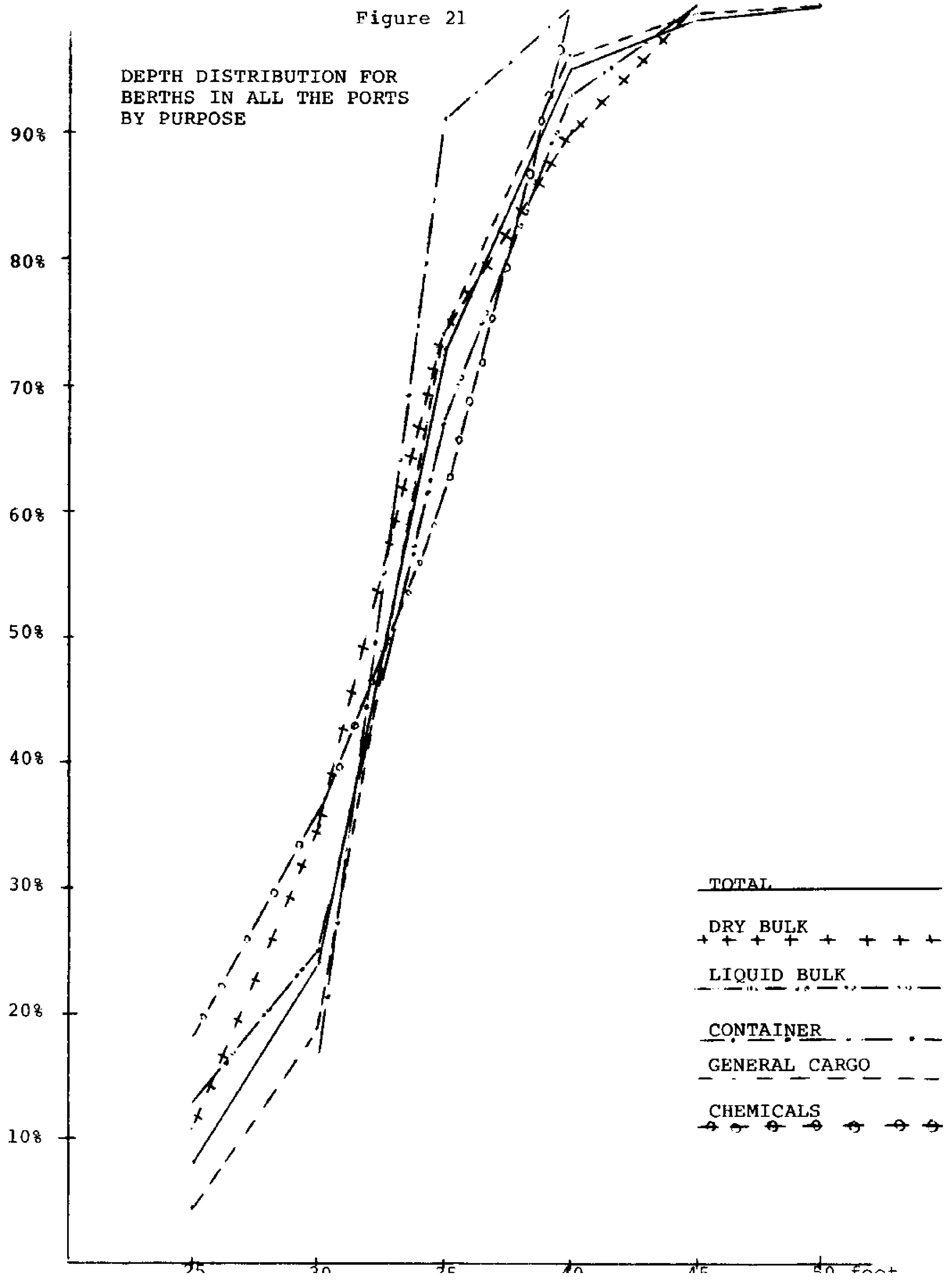

DEPTH DISTRIBUTION FOR BERTHS IN ALL THE PORTS BY PURPOSE
90%
80%
70%
60%
50%
40%
30%
20%
10%
TOTAL
DRY BULK
LIQUID BULK
CONTAINER
GENERAL CARGO
CHEMICALS

Table No. 3

NUMBER OF WHARFS, BERTHS SPACE, RAILROAD CONNECTION FOR EACH PORT

	Total No. of Wharfs		No. of Margins		No. of Fin. Piers		SDM of Berth Len.		No. with RR Con.	
	No.	%	No.	%	No.	%	103 ft.	%	No.	%
New York	250	42.0	139		111		300.5	45.4	117	
Baltimore	88	14.5	41		47		96.3	14.6	80	
Jacksonville	32	5.0	28		4		19.7	3.0	30	
Portland	19	3.2	12		7		14.7	2.6	16	
Boston	51	8.5	39		12		38.2	5.8	38	
Providence	18	3.0	13		5		14.5	2.2	16	
New Haven	13	2.2	10		3		7.9	1.2	10	
Delaware River	94	15.6	46		48		119.7	18.1	84	
Hampton Roads	36	6.0	19		17		46.9	7.1	34	
Total	601	100.0	347		254		658.4	100.0	425	

TABLE 4

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

PORT OF: New York

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
General Cargo	21	85	106		187.223	62.4
Containers	3	2	5		8.401	2.8
Fruit	1	--	1		1.000	0.3
Grain	--	--	--	--	--	
Sugar	5	1	6		3.688	1.2
Paper	4	1	5		2.549	0.9
Lumber	4	2	6		4.615	1.5
Copper	3	3	6		4.623	1.5
Gypsum Rock	2	2	4		2.460	0.8
Cement	11	2	13		4.827	1.6
Coal	9	-	9		7.158	2.5
Misc. Dry Bulk	9	3	12		12.429	3.7
Chemicals	16	3	19		9.764	3.2
Oil Handling	51	9	60		51.726	17.6
Total	139	113	252		300.463	

TABLE 5

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

(AGGREGATE) PORT OF: New York

	Marginal	Finger	Total	%	Berth Space	%
Dry Bulk	47	14	60	24	42,349	14
Liquid Bulk	51	9	60	24	51,726	17
Containers	3	2	5	2	8,401	3
General Cargo	22	85	107	42	188,223	63
Chemicals	16	3	19	8	9,764	3
Total	139	113	252	100	300,463	100.0

TABLE 6

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

PORT OF: Baltimore

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
General Cargo	18	12	30		40,700	42.3
Containers	1	--	1		700	0.7
Fruit	1	--	1		713	0.7
Grain	1	2	3		5,623	5.8
Sugar	1	1	2		1,460	1.5
Paper	1	--	1		240	0.3
Lumber	--	1	1		1,195	1.2
Copper	--	2	2		2,450	2.5
Gypsum Rock	2	--	2		1,315	1.4
Cement	1	--	1		450	0.5
Coal	--	3	3		5,719	6.0
Misc. Dry Bulk	8	9	17		22,319	23.2
Chemicals	4	5	9		6,739	7.0
Oil Handling	3	12	15		6,693	6.9
Total	41	47	88		96,316	100.0

TABLE 7

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

(AGGREGATE) PORT OF: Baltimore

	Marginal	Finger	Total	%	Berth Space	%
Dry Bulk	14	18	32		41,413	43.0
Liquid Bulk	3	12	15		6,693	7.0
Containers	1	--	1		700	0.7
General Cargo	19	12	31		40,771	42.3
Chemicals	4	5	9		6,739	7.0
Total	41	47	88		96,316	100.0

TABLE 8

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

PORT OF: Jacksonville

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
General Cargo	12	2	14		11,470	58.4
Containers	1	-	1		1,200	6.1
Fruit	-	-	-		------	----
Grain	-	-	-		------	----
Sugar	-	-	-		------	----
Paper	-	-	-		------	----
Lumber	-	-	-		------	----
Copper	-	-	-		------	----
Gypsum Rock	1	1	2		1,045	5.3
Cement	-	-	-		------	----
Coal	-	-	-		------	----
Misc. Dry Bulk	2	-	2		1.420	7.2
Chemicals	-	-	-		------	----
Oil Handling	12	1	13		4.529	23.0
Total	28	4	32		19,664	100.0

TABLE 9

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

(AGGREGATE) PORT OF: Jacksonville

	Marginal	Finger	Total	%	Berth Space	%
Dry Bulk	3	1	4		2,465	12.5
Liquid Bulk	12	1	13		4,529	23.0
Containers	1	-	1		1,200	6.1
General Cargo	12	2	14		11,470	58.4
Chemicals	-	-	-		-----	----
Total	28	4	32		19,664	100.0

TABLE 10

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

PORT OF: Portland

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
General Cargo	1	3	4		5,093	34.6
Containers	-	-	-		---	
Fruit	-	-	-		---	
Grain	-	-	-		---	
Sugar	-	-	-		---	
Paper	-	-	-		---	
Lumber	-	-	-		---	
Copper	-	-	-		---	
Gypsum Rock	-	-	-		---	
Cement	-	-	-		---	
Coal	-	-	-		---	
Misc. Dry Bulk	2	1	3		2,655	18.1
Chemicals	-	-	-		---	
Oil Handling	9	3	12		6,969	47.3
Total	12	7	19		14,717	100.0

TABLE 11

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

(AGGREGATE) PORT OF: Portland

	Marginal	Finger	Total	%	Berth Space	%
Dry Bulk	2	1	3		2,655	18.1
Liquid Bulk	9	3	12		6,969	47.3
Containers	-	-	-		-----	
General Cargo	1	3	4		5,093	34.6
Chemicals	-	-	-		-----	
Total	12	7	19		14,717	100.0

TABLE 12

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

PORT OF: Boston

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
General Cargo	8	8	16		21,350	55.8
Containers	1	-	1		550	1.4
Fruit	-	-	-		------	
Grain	-	-	-		------	
Sugar	2	-	2		800	2.1
Paper	-	-	-		------	
Lumber	-	-	-		------	
Copper	-	-	-		------	
Gypsum Rock	1	-	1		550	1.4
Cement	1	-	1		200	0.5
Coal	-	-	-		------	
Misc. Dry Bulk	4	-	4		2,400	6.3
Chemicals	3	-	3		2,150	5.7
Oil Handling	19	4	23		10,250	26.8
Total	39	12	51		38,250	100.0

TABLE 13

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

(AGGREGATE) PORT OF: Boston

	Marginal	Finger	Total	%	Berth Space	%
Dry Bulk	8	-	8		3,950	10.3
Liquid Bulk	19	4	23		10,250	26.8
Containers	1	-	1		550	1.4
General Cargo	8	8	16		21,350	55.8
Chemicals	3	-	3		2,150	5.7
Total	39	12	51		38,250	100.0

TABLE 14

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

PORT OF: Hampton Roads

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
General Cargo	6	12	18		28,861	61.5
Containers	-	--	--		------	
Fruit	-	--	--		------	
Grain	2	--	2		1,662	3.5
Sugar	-	--	--		------	
Paper	-	--	--		------	
Lumber	1	--	1		400	0.9
Copper	-	--	--		------	
Gypsum Rock	-	--	--		------	
Cement	-	--	--		------	
Coal	-	4	4		9,760	20.8
Misc. Dry Bulk	-	1	1		1,197	2.5
Chemicals	-	--	--		------	
Oil Handling	10	--	10		5,047	10.8
Total	19	17	36		46,927	100.0

TABLE 15

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

(AGGREGATE) PORT OF: Hampton Roads

	Marginal	Finger	Total	%	Berth Space	%
Dry Bulk	3	5	8		13,019	27.7
Liquid Bulk	10	-	10		5,047	10.8
Containers	-	-	-		------	
General Cargo	6	12	18		28,861	61.5
Chemicals	-	-	-		------	
Total	19	17	36		46,927	100.0

TABLE 16

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

PORT OF: Delaware River

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
General Cargo	7	22	29		53,760	45.0
Containers	2	--	2		1,400	1.2
Fruit	-	-	-		------	
Grain	-	2	2		3,085	2.6
Sugar	2	4	6		12,512	10.4
Paper	-	--	--		------	
Lumber	-	--	--		------	
Copper	-	--	--		------	
Gypsum Rock	4	--	4		2,082	1.7
Cement	-	--	--		------	
Coal	-	3	3		3,287	2.7
Misc. Dry Bulk	4	7	11		12,983	10.9
Chemicals	8	2	10		4,710	3.9
Oil Handling	19	8	27		25,880	21.6
Total	46	48	94		119,699	100.0

TABLE 17

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

(AGGREGATE) PORT OF: Delaware River

	Marginal	Finger	Total	%	Berth Space	%
Dry Bulk	10	16	26		33,949	28.3
Liquid Bulk	19	8	27		25,880	21.6
Containers	2	--	2		1,400	1.2
General Cargo	7	22	29		53,760	45.0
Chemicals	8	2	10		4,710	3.9
Total	46	48	94		119,699	100.0

TABLE 18

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

PORT OF: New Haven

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
General Cargo	1	1	2		1,640	20.9
Containers	-	-	-		-----	
Fruit	-	-	-		-----	
Grain	-	-	-		-----	
Sugar	-	-	-		-----	
Paper	-	-	-		-----	
Lumber	-	-	-		-----	
Copper	-	-	-		-----	
Gypsum Rock	-	-	-		-----	
Cement	-	-	-		-----	
Coal	-	-	-		-----	
Misc. Dry Bulk	-	1	1		780	10.0
Chemicals	-	-	-		-----	
Oil Handling	9	1	10		5,434	69.1
Total	10	3	13		7,854	100.0

TABLE 19

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

(AGGREGATE) PORT OF: New Haven

	Marginal	Finger	Total	%	Berth Space	%
Dry Bulk	-	1	1		780	10.0
Liquid Bulk	9	1	10		5,434	69.1
Containers	-	-	-		-----	
General Cargo	1	1	2		1,640	20.9
Chemicals	-	-	-		-----	
Total	10	3	13		7,854	100.0

TABLE 20

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

PORT OF: Providence

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
General Cargo	2	-	2		4,662	32.2
Containers	-	-	-		-----	
Fruit	-	-	-		-----	
Grain	-	-	-		-----	
Sugar	-	-	-		-----	
Paper	-	-	-		-----	
Lumber	-	-	-		-----	
Copper	-	-	-		-----	
Gypsum Rock	-	-	-		-----	
Cement	3	-	3		1,160	8.0
Coal	-	-	-		-----	
Misc. Dry Bulk	1	-	1		400	2.8
Chemicals	-	1	1		345	2.4
Oil Handling	7	4	11		7,924	54.6
Total	13	5	18		14,491	100.0

TABLE 21

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PURPOSE OR USE

(AGGREGATE) PORT OF: Providence

	Marginal	Finger	Total	%	Berth Space	%
Dry Bulk	4	-	4		1,560	10.8
Liquid Bulk	7	4	11		7,924	54.6
Containers	-	-	-		-----	
General Cargo	2	-	2		4,662	32.2
Chemicals	-	1	1		345	2.4
Total	13	5	18		14,491	100.0

Table No. 22

NUMBER OF WHARFS, SIZE OF BERTH, LENGTH, RAILROAD CONNECTIONS FOR EACH TYPE OF CARGO

	Total No. of Wharfs		No. of Marginal		No. of Finger		Berth Space		No. With RR Conn.	
	No.	%	No.	%	No.	%		%	No.	%
General Cargo	221	36.8	76		145		354.8	53.9	143	
Containers	10	1.7	18		2		12.2	2.0	6	
Fruit	2	0.3	2				1.7	0.3	2	
Grain	7	1.2	3		4		10.4	1.6	7	
Sugar	16	2.7	10		6		18.5	2.8	9	
Paper	6	4.0	5		1		2.8	0.4	[illegible]	
Lumber	8	1.3	5		3		6.2	0.9	5	
Copper	8	1.3	3		5		7.1	1.1	7	
Gypsum Rock	11	1.8	10		1		7.5	1.1	13	
Cement	18	3.0	16		2		6.6	1.0	6	
Misc. Dry Bulk	52	8.7	30		22		56.6	8.6	48	
Chemicals	42	7.0	31		11		23.7	3.6	38	
Oil Handling	181	30.0	139		42		124.5	18.9	126	
Coal	19	3.2	9		10		25.9	3.9	15	
Total	601	100.0	347		254		658.4	100.0	425	

TABLE 23

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PORTS

PURPOSE OF USE: GENERAL CARGO

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
New York	21	85	106		187.223	52.7
Baltimore	18	12	30		40.700	11.5
Jacksonville	12	2	14		11.470	3.3
Portland	1	3	4		5.093	1.4
Boston	6	8	16		21.350	6.0
Providence	2	-	2		4.662	1.3
New Haven	1	1	2		1.640	0.5
Delaware River		22	29		53.760	15.3
Hampton Roads	5	[illegible]	13		28.961	8.1
Total	[illegible]	[illegible]	[illegible]		[illegible]	100.0

TABLE 24

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PORTS

PURPOSE OF USE: CONTAINERS (1970)

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
New York	3	2	5		8.401	68.6
Baltimore	1	-	1		.700	5.7
Jacksonville	1	-	1		1.200	9.8
Portland	-	-	-		---	---
Boston	4	-	1		.550	4.5
Providence	-	-	-		---	---
New Haven	-	-	-		---	---
Delaware River	2	-	2		1.400	11.4
Hampton Roads	-	-	-		---	---
Total	8	2	10		12.251	100.0

TABLE 25

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PORTS

PURPOSE OF USE: FRUIT

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
New York	1	-	1		[illegible]	[illegible]
Baltimore	1	-	1		[illegible]	[illegible]
Jacksonville	-	-	-		---	---
Portland	-	-	-		---	---
Boston	-	-	-		---	---
Providence	-	-	-		---	---
New Haven	-	-	-		---	---
Delaware River	-	-	-		---	---
Hampton Roads	-	-	-		---	---
Total	[illegible]	-	[illegible]		[illegible]	[illegible]

TABLE 26

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PORTS

PURPOSE OF USE: Grain

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
New York	-	-	-		-----	
Baltimore	1	2	3		5,623	54.2
Jacksonville	-	-	-		-----	
Portland	-	-	.		-----	
Boston	-	-			-----	
Providence		-	-		-----	
New Haven	-	-	-		-----	
Delaware River	-	2	2		3,085	29.8
Hampton Roads	2	-	2		1,662	16.0
Total	3	4	7		10,370	100.0

TABLE 27

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PORTS

PURPOSE OF USE: SUGAR

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
New York	5	1	6		3.688	20.0
Baltimore	1	1	2		1.460	7.9
Jacksonville	-	-	-		---	---
Portland	-	-	-		---	---
Boston	2	-	2		.800	4.3
Providence	-	-	-		---	-
New Haven	-	-	-		---	---
Delaware River	2	4	6		12.512	67.9
Hampton Roads	-	-	-		---	---
Total	10	6	16		13.460	

TABLE 28

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PORTS

PURPOSE OF USE: PAPER

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
New York	4	1	5		2.549	91.4
Baltimore	1	-	1		.240	8.6
Jacksonville	-	-	-		---	--
Portland	-	-	-		---	--
Boston	-	-	-		---	--
Providence	-	-	-		---	--
New Haven	-	-	-		---	--
Delaware River	-	-	-		---	--
Hampton Roads	-	-	-		---	--
Total	5	1	6		2.789	100.0

TABLE 29

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PORTS

PURPOSE OF USE: LUMBERS

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
New York	4	2	6		4.615	74.4
Baltimore	-	1	1		1.195	19.2
Jacksonville	-	-	-		---	---
Portland	-	-	-		---	---
Boston	-	-	-		---	---
Providence	-	-	-		---	---
New Haven	-	-	-		---	---
Delaware River	-	-	-		---	---
Hampton Roads	1	-	1		.400	6.4
Total	5	3	8		6.210	100.0

TABLE 30

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PORTS

PURPOSE OF USE: COPPER

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
New York	3	3	6		4.623	65.4
Baltimore	-	2	2		2.450	34.6
Jacksonville	-	-	-		---	---
Portland	-	-	-		---	---
Boston	-	-	-		---	---
Providence	-	-	-		---	---
New Haven	-	-	-		---	---
Delaware River	-	-	-		---	---
Hampton Roads	-	-	-		---	---
Total	3	5	8		7.073	100.0

TABLE 31

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PORTS

PURPOSE OF USE: GYPSUM ROCK

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
New York	2	-	2		2.460	33.0
Baltimore	2	-	2		1.315	17.6
Jacksonville	1	1	2		1.045	14.0
Portland	-	-	-		---	---
Boston	1	-	1		.550	7.4
Providence	-	-	-		---	---
New Haven	-	-	-		---	---
Delaware River	4	-	4		2.082	28.0
Hampton Roads	-	-	-		---	---
Total	10	1	11		7.452	100.[illegible]

TABLE 32

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PORTS

PURPOSE OF USE: CEMENT AND BUILDING MATERIALS (BULK)

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
New York	11	2	13		4.824	72.7
Baltimore	1	-	1		.450	6.8
Jacksonville	-	-	-		---	---
Portland	-	-	-		---	---
Boston	1	-	1		.200	3.0
Providence	3	-	3		1.160	17.5
New Haven	-	-	-		---	---
Delaware River	-	-	-		---	---
Hampton Roads	-	-	-		---	---
Total	16	2	18		6.637	100.0

TABLE 33

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PORTS

PURPOSE OF USE: COAL

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
New York	9	-	9		7.158	27.6
Baltimore	-	3	3		5.719	22.1
Jacksonville	-	-	-		---	---
Portland	-	-	-		---	---
Boston	-	-	-		---	---
Providence	-	-	-		---	---
New Haven	-	-	-		---	---
Delaware River	-	3	3		3.287	12.6
Hampton Roads	-	4	4		9.760	37.7
Total	9	10	19		25.924	100.0

TABLE 36

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PORTS

PURPOSE OF USE: OIL HANDLING

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
New York	51	9	60		51.726	41.6
Baltimore	3	12	15		6.693	5.4
Jacksonville	12	1	13		4.529	3.6
Portland	[illegible]	[illegible]	17		6.949	[illegible]
Boston	19	4	23		10.750	8.7
Providence	7	4	11		7.924	6.4
New Haven	9	[illegible]	[illegible]		5.434	[illegible]
Delaware River	19	8	27		25.880	20.8
Hampton Roads	10	-	10		5.047	4.1
Total	139	42	181		124.452	100.0

TABLE 35

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PORTS

PURPOSE OF USE: CHEMICALS

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
New York	16	3	19		9.764	41.2
Baltimore	4	5	9		6.739	28.4
Jacksonville	-	-	-		---	---
Portland	-	-	-		---	---
Boston	3	-	3		2.150	9.1
Providence	-	1	1		.345	1.5
New Haven		-	-		---	---
Delaware River	8	2	10		4.710	19.8
Hampton Roads	-	-	-		---	---
Total	31	11	42		23.708	

TABLE 34

CHARACTERISTICS OF THE BERTHS CLASSIFIED BY PORTS

PURPOSE OF USE: MISC. DRY BULK

	Marginal	Finger	Total		Berth Space	
	No.	No.	No.	%	(feet)	%
New York	9	5	[illegible]		[illegible]	[illegible]
Baltimore	8	9	17		[illegible]	[illegible]
Jacksonville	2	-	2		[illegible]	[illegible]
Portland	7	-	[illegible]		[illegible]	[illegible]
Boston	4	-	4		[illegible]	[illegible]
Providence	1	-	1		[illegible]	-
New Haven	-	[illegible]			-	[illegible]
Delaware River	4	-	[illegible]		[illegible]	[illegible]
Hampton Roads	-	-	1		[illegible]	[illegible]
Total	30	22	52		56.55[illegible]	

Table No. 37

RAILROAD CONNECTION BY PURPOSE OF BERTH

		N.Y.	%	Balt.	%	J'kville	%	Port.	%	Bos.	%	Prov.	%	N.H.	%	Del R	%	Hmp Rds	%	Tot	%
General Cargo	a)	29	27.	30	100	14	100	3	75	16	100	2	100	2	100	29	100	18	100	143	65
	b)	106		30		14		4		16		2		2		29		18		221	
Containers	a)	3	60	1	100					1	100					1	50			6	75
	b)	5		1						1						2				8	
Fruit	a)	1	100	1	100															1	100
	b)	1		1																1	
Grain	a)			3	100											2	100	2	100	7	100
	b)			3												2		2		7	
Sugar	a)	1	17	2	100											6	100			9	56
	b)	6		2						2						6				16	
Paper	a)	2	40	1	100															3	50
	b)	5		1																6	
Lumber	a)	3	50	1	100													1	100	5	62
	b)	6		1														1		8	
Copper	a)	6	100	1	50															7	87
	b)	6		2																8	
Gypsom Rock	a)	2	100	2	100	2	100			1	100					4	100			11	100
	b)	2		2		2				1						4				11	
Cement	a)	4	31	1	100							1	33							6	33
	b)	13		1						1		3								18	
Coal	a)	5	55	3	100											3	100	4	100	15	71
	b)	9		3												3		4		19	
Misc. Dry Bulk	a)	11	92	17	100	2	100	3	100	2	50	1	100	1	100	10	91	1	100	48	94
	b)	12		17		2		3		4		1		1		11		1		52	
Chemicals	a)	17	90	9	100					3	100	1	100			8	80			38	90
	b)	19		9						3		1				10				42	
Oil Handling	a)	33	55	8	53	12	92	10	83	15	65	11	100	7	70	22	81	8	80	126	70
	b)	60		15		13		12		23		11		10		27		10		181	
tal	a)	117	47	80	91	30	94	16	84	38	75	16	89	10	77	84	90	34	95	426	71
	b)	250		88		32		19		51		18		13		94		36		601	

Note: a) No. of piers with railroad connections
b) Total no. of piers

Table No 38

STORAGE CAPACITY AT THE WHARFS, BY PORT

	Transit Sheds (10^3 ft^2) (a)	Open Space 10^3 ft^2 (a)	Tanks (Oil) 10^3 Barrels	Silos (Grain) 10^3 Bushels
New York	16.018	3.659	99.206	12.837
Baltimore	2.360	4.150	16.664	
Jacksonville	1.096	1.526	6.630	
Portland	460		8.037	
Boston	3.975	2.059	17.000	
Providence	137	3.488	9.111	
New Haven			6.362	
Delaware River	2.749	11.761	53.920	4.724
Hampton Roads	2.536		5.230	8.750
Total	29.331	26.640	222.160	26.311

(a) General Cargo Only

Table No. 39
INDEPENDENT STORAGE AREA BY PORTS

	Dry 10^3 ft^2	Cool and Freeze 10^3 ft^2	Open 10^3 ft^2
New York	15.988	27.563	7.283
Baltimore	4.295	4.065	13.520
Jacksonville	2.534	2.978	5.886
Portland	196	4.563	861
Boston	2.874	11.422	2.087
Providence	.120	1.615	
New Haven	.142	.353	.698
Delaware River	8.660	12.555	5.782
Hampton Road			
Total	34.809	65.114	36.117

Table No. 40

NUMBER OF BERTH AND LENGTH DISTRIBUTION FOR EACH PORT

	300 400	400 500	500 600	600 700	700 800	800 900	900 1000	1000 1500	1500 2000	2000+	Total
New York	39	31	42	42	46	18	19	75	6	6	324
	39	70	112	154	200	218	237	212	318	324	
	12.0	21.6	34.3	47.5	67.0	67.5	73.3	97.0	98.0	100.0	
Baltimore	10	11	10	10	10	14	15	18	3	2	103
	10	21	31	41	51	65	80	98	101	103	
	10.0	19.6	30.5	39.8	49.0	63.0	77.5	95.0	98.0	100.0	
Jacksonville	4	4	2	2	2	1	2	5	1		23
	4	8	10	12	14	15	17	22	23	23	
	17.4	34.8	43.5	52.3	61.0	65.3	74.	95.5	100.0	100.0	
Portland	3	5	4	2			1	2	2		19
	3	8	12	14	14	14	15	17	19	19	
	15.8	42.0	63.0	73.5	73.5	73.5	78.9	89.5	100.0	100.0	
Boston	8	6	10	9	5	4	2	7	1		52
	8	14	24	33	38	42	44	51	52	52	
	15.4	27.0	46.0	63.5	73.0	80.0	85.0	98.0	100.0	100.0	
Providence	2	1	6	5	1			1	2		18
	2	3	9	14	15	15	15	16	18	18	
	11.2	16.6	50.0	77.5	83.0	83.0	83.0	89.0	100.0	100.0	
New Haven	2	3	3	1	2						11
	2	5	8	9	11	11	11	11	11	11	
	18.2	45.5	72.7	87.0	100.	100.	100.	100.	100.	100.	
Hampton Rds.	4	8	4	5	4	5		22			52
	4	12	16	21	25	30	30	52		52	
	77.	23.0	30.8	38.8	48.0	57.8	57.8	100.0	100.0	100.0	
Delaware R.	7	12	26	10	14	10	6	17	3	4	109
	7	19	45	55	69	79	85	102	105	109	
	6.4	17.4	41.2	50.5	63.3	72.5	78.0	93.5	97.2	100.0	
Total No. of Berths	79	81	107	86	84	52	45	147	18	12	711
Total Accumulated	79	160	267	353	437	489	534	681	699	711	
	11.1	22.5	37.5	50.0	61.5	68.8	75.0	95.5	97.0	100.0	

Table No. 41

NUMBER OF BERTH AND LENGTH DISTRIBUTION, FOR EACH TYPE OF CARGO

	300 400	400 500	500 600	600 700	700 800	800 900	900 1000	1000 1500	1500 2000	+2000	Total
General Cargo	33	26	62	48	49	29	32	105	13	16	403
	33	59	121	169	218	247	279	384	397	403	
	7.6	14.3	30.0	42.0	54.5	61.6	69.5	95.0	98.5	100.0	
Containerized Cargo *	1		1	2	2	1	2	1		2	12
	1	1	2	4	6	7	9	10	10	12	
	8.2	8.2	16.5	33.5	50.0	58.3	75.0	82.0	82.0	100.0	
Fruit					1			1			2
					1	4	4	2	2	2	
					50.0	50.0	50.0	100.0	100.0	100.0	
Grain				1		3		4			8
				1	1	4	4	8	8	8	
				12.5	12.5	50.0	50.0	100.0	100.0	100.0	
Sugar	1	5	2		2	1	1				12
	1	6	8	8	10	11	12	12	12	12	
	8.4	50.0	66.7	66.7	83.5	91.5	100.0	100.0	100.0	100.0	
Paper		1	2	1							4
		1	3	4	4	4	4	4	4	4	
		25.0	75.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
ber	1	2	4					1			8
	1	3	7	7	7	7	7	8	8	8	
	12.5	37.5	87.5	87.5	87.5	87.5	87.5	100.0	100.0	100.0	
Copper	2	2		1	2						7
	2	4	4	5	7	7	7	7	7	7	
	28.6	37.2	57.2	71.5	100.0	100.0	100.0	100.0	100.0	100.0	
Gypsum Rock		5	2	3	1			1			12
		5	7	10	11	11	11	12	12	12	
		41.5	58.5	83.0	91.5	9.15	91.5	100.0	100.0	100.0	
Cement	1	1	1								3
	1	2	3	3	3	3	3	3	3	3	
	33.3	66.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
Misc. Dry Bulk	5	5	3	7	9	7	1	13	1	2	53
	5	10	13	20	29	36	37	50	51	53	
	4.5	18.9	24.5	37.8	55.0	63.0	70.0	94.5	96.0	100.0	
Chemicals	7	7	4	2	2	5	1				28
	7	14	18	20	22	27	28	28	28	28	
	25.0	50.0	64.2	71.5	78.5	71.5	100.0	100.0	100.0	100.0	
Oil Handling	28	26	25	20	14	4	4	12	4	2	134
	28	54	79	99	113	117	121	133	137	139	
	20.5	38.8	56.8	71.0	81.0	84.0	87.0	95.5	98.5	100.0	
Coal		1	1	1	2	2	4	9			20
		1	2	3	5	7	11	20	20	20	
		5.0	100	15.0	25.0	35.0	55.0	100.0	100.0	100.0	
Total	79	81	107	86	84	52	45	147	18	12	711
[illegible]	79	160	267	353	437	489	534	681	699	711	
%	11.1	22.5	37.5	50.0	61.5	68.8	75.0	95.5	97.0	100.0	

*Exclude proprietary terminals

Table No. 42

NUMBER OF BERTH AND LENGTH DISTRIBUTION
BY (AGGREGATE) PURPOSE

	300 400	400 500	500 600	600 700	700 800	800 900	900 1000	1000 1500	1500 2000	+2000	Total
	10.0	22.0	15.0	14.0	16.0	13.0	6.0	28.0	1.0	2.0	127
Dry Bulk	10.0	32.0	47.0	16.0	77.0	90.0	96.0	124.0	125.0	127.0	
	8.0	25.0	37.0	48.0	60.0	71.0	76.0	97.0	98.0	100.0	
	28.0	26.0	25.0	20.0	14.0	4.0	4.0	12.0	4.0	2.0	139
Liquid Bulk	28.0	54.0	79.0	99.0	113.0	117.0	121.0	133.0	137.0	139.0	
	20.5	38.8	56.8	71.0	81.0	84.0	87.0	95.5	98.5	100.0	
	* 1.0	-	1.0	2.0	2.0	1.0	2.0	1.0	-	2.0	12
Containers	1.0	1.0	2.0	4.0	6.0	7.0	9.0	10.0	10.0	12.0	
	8.0	8.0	16.0	33.0	50.0	58.0	75.0	82.0	82.0	100.0	
General	33.0	26.0	62.0	48.0	50.0	29.0	32.0	106.0	13.0	6.0	405
Cargo	33.0	59.0	121.0	169.0	219.0	248.0	280.0	386.0	399.0	405.0	
	8.0	15.0	30.0	42.0	55.0	62.0	70.0	95.0	98.0	100.0	
	7.0	7.0	4.0	2.0	2.0	5.0	1.0	-	-	-	28
Chemicals	7.0	14.0	18.0	20.0	22.0	27.0	28.0	28.0	28.0	28.0	
	25.0	50.0	64.2	71.5	78.5	96.5	100.0	100.0	100.0	100.0	
	79.0	81.0	107.0	86.0	84.0	52.0	45.0	147.0	18.0	12.0	711
Total	79.0	160.0	267.0	353.0	437.0	439.0	534.0	681.0	699.0	711.0	
	11.1	22.5	37.5	50.0	61.5	68.8	75.0	95.5	97.0	100.0	

* Excludes proprietary terminals

Table No. 43

NUMBER OF BERTH AND DEPTH DISTRIBUTION FOR EACH PORT

	20 25	25 30	30 35	35 40	40 45	45 50	+50	Total
	26	59	167	64	5	3		324
New York	26	85	252	316	321	324	324	
	8.0	36.2	78.2	97.5	99.0	100.0	100.0	
	7	20	53	15	8			103
Baltimore	7	27	80	85	103	103	103	
	6.8	26.2	78.0	92.5	100.0	100.0	100.0	
	3	7	12	1				23
Jacksonville	3	10	22	23	23	23	23	
	13.0	42.5	95.5	100.0	100.0	100.0	100.0	
	2		6	7	4			19
Portland	2	2	8	15	19	19	19	
	10.5	10.5	42.0	79.0	100.0	100.0	100.0	
	2	3	16	26	5			52
Boston	2	5	21	47	52	52	52	
	3.8	9.6	40.0	91.0	100.0	100.0	100.0	
	2		14	2				18
Providence	2	2	16	18	18	18	18	
	11.1	11.1	89.0	100.0	100.0	100.0	100.0	
	2	2	4	3				11
New Haven	2	4	8	11	11	11	11	
	18.2	36.4	73.0	100.0	100.0	100.0	100.0	
	9	20	54	19	7			109
Delaware River	9	29	83	102	109	109	109	
	8.2	26.6	76.0	93.5	100.0	100.0	100.0	
	2	3	26	14	7			52
Hampton Roads	2	5	31	45	52	52	52	
	3.8	9.6	59.5	86.5	100.0	100.0	100.0	
	55	114	352	151	36	3		711
Total No. Berths	55	169	521	672	708	711	711	
	7.7	23.7	73.0	94.5	99.5	100.0	100.0	

* Excludes proprietary container terminals

TABLE NO. 44

NUMBER OF BERTH AND DEPTH DISTRIBUTION FOR EACH TYPE OF CARGO

	20 25	25 30	30 35	35 40	40 45	45 50	+50	Total
General Cargo	18	56	225	88	13	3		403
	18	74	299	387	398	403	403	
	4.5	18.4	72.5	96.0	98.5	100	100	
Container Cargo *		2	9	1				12
		2	11	12	12	12	12	
		11	91.	100	100	100	100	
Fruit		1	1					2
		1	2	2	2	2	2	
		100	100	100	100	100	100	
Grain			3	3	2			8
			3	6	8	8	8	
			37.5	75.0	100	100	100	
Sugar	1	4	6	1				12
	4	5	11	12	12	12	12	
	8.3	41.5	91.5	100	100	100	100	
Paper	1		3					4
	1	1	4	4	4	4	4	
	25.0	25.0	100	100	100	100	100	
Lumber	2	4	2					8
	2	6	8	8	8	8	8	
	25.0	75.0	100	100	100	100	100	
Copper		1	3	3				7
		1	4	7	7	7	7	
		14.3	37.2	100	100	100	100	
Gypsum Rock	3	3	6					12
	3	6	12	12	12	12	12	
	25.0	50.0	100	100	100	100	100	
Cement		2	1					3
		2	3	3	3	3	3	
		66.6	100	100	100	100	100	
Coal	2	4	4	5	5			20
	2	6	10	15	20	20	20	
	10.0	30.0	50.0	75.0	100	100	100	
Misc. Dry Bulk	5	12	22	8	6			53
	5	17	39	47	53	53	53	
	9.5	32.1	73.5	98.5	100	100	100	
Chemicals	5	8	9	6				20
	5	13	22	28	28	28	28	
	17.8	35.8	60.6	100	100	100	100	
Oil Handling	18	17	58	36	10			139
	18	35	93	129	139	139	139	
	13.0	25.1	67.0	93.0	100	100	100	
Total Berths	55	114	352	151	36	3		711
ACC	55	169	521	672	708	711	711	
	7.7	23.7	73.0	94.5	99.5	100	100	

* Excludes proprietary terminals

TABLE NO. 45

NUMBER OF BERTH AND DEPTH DISTRIBUTION BY PURPOSE

	20 25	25 30	30 35	35 40	40 45	45 50	+50	Total
Dry Bulk	14 14 11	30 44 35	30 94 74.	20 114 90	13 127 100	 127 100	 127 100	127
Liquid Bulk	18 18 13.	17 35 25.	58 93 67.	36 129 93.	10 139 100.	 139 100	 139 100	139
Containers *		2 2 17	9 11 91.	1 12 100	 12 100	 12 100	 12 100	12
General Cargo	18 18 4.4	57 76 18.8	226 301 74.0	88 389 96.0	13 402 99.5	3 405 100	 405 100	405
Chemicals	5 5 12	8 13 36.	9 22 61.	6 28 100.	 28 100.	 28 100.	 28 100.	28
Total	55 55 8.	114 169 24.	352 521 73.	151 672 95.	36 708 99.	3 711 100.	 711 100.	711

* Excludes proprietary terminals

Table No. 46

SHEETS AREA FOR CARDS – LENGTH INSTRUCTION

	800 400	400 500	500 600	600 700	700 800	800 900	900 1000	1000 1500	1500 2000	4000	Total
-50		3	6	2	1		2	3			17
50-100			8	3	4	5	4	5			29
100-150			2	1	5	3	3	8	1		23
150-200			1	6	7	3	3	13	1		34
200-250				4	2	1	1	8	1		17
250-300				1	1			9			11
300						1	1	5			7
SUM		3	17	17	20	13	14	51	3		138
Marginal											
-50		5	2		2		2	2	2		15
50-100		2	1	1	1			1	1	1	8
100-150			1				1	4	3		9
150-200			1				1	2	1		5
200-250			1					2		1	4
250-300								2			5
300				1				2	1	3	4
SUM		7	6	2	3		4	15	8	5	50
Finger & Marginal		10	23	19	23	13	18	66	11	5	188

Table No. 47

TANK CAPACITY - LENGTH DISTRIBUTION

	300 400	400 500	500 600	600 700	700 800	800 900	900 1000	1000 1500	1500 2000	+2000	Total
-250			1								1
250-500		4	3			1	1				9
500-1000		2	1		1		1				5
1000-2000		3	2	3	2		1	1			12
2000-4000								1	1		2
4000-8000					1				1		2
8000											
SUM		9	7	3	4	1	3	3	[illegible]		31
Marginal											
-250	6	6	3	5	1						21
250-500	2	2	1	3				1			9
500-1000	4	1	3	3	2	3	1	1			18
1000-2000	2	1		3	5	1		1	1		14
2000-4000	2	2	1	1				2		1	9
4000-8000			2		1			4		1	8
8000-								1			1
SUM	16	12	10	15	9	4	1	10	1	2	80
Finger & Marginal	16	21	17	18	13	5	4	13	2	2	111

Table 48

NUMBER OF BERTH SPACE UNITS DEPTH-LENGTH-DISTRIBUTION

GENERAL CARGO WHARFS _ NEW YORK

	300 400	400 500	500 600	600 700	700 800	800 900	900 1000	1000 1500	1500 2000	2000	Total
20/25					1		2		1		4
25/30		3	1	2	5	3	5	9	1		29
30/35	9	6	16	16	24	4	5	38	3	2	123
35/40	6		1	7	6	4	2	11		1	38
40/45			1			1		2			4
45/50			1					2			3
50/-											
Total	15	9	20	25	36	12	14	62	6	3	201

4.0 PORT CAPACITY MEASURES AND OPTIMAL PORT CAPACITY

4.1 Introduction

For the purpose of port planning, questions of optimal capacity arise in several contexts. One of these is a short run question; given a particular port design (and its consequent physical capacity), how many vehicles (ships, land transport) or equivalently, how many cargo or passenger units could be served. Another is the long run question; given projected demand for service, what port design should be built or to what level should the port be expanded.

Economic analysis provides the criteria of economic efficiency which can be used to determine a level of economic capacity in these two cases. The short run case corresponds to short run equilibrium through an appropriate choice of port operating variables and pricing. The long range decision corresponds to the appropriate choice of scale of plant and choice of design variables of the port determined through investment analysis.

To provide the background in development of a framework and methodology for the selection of measures of "optimal" design of ports and for the evaluation of port "efficiency", production effectiveness or profitability, various approaches to the establishment of port capacity measures were reviewed. *

* Rallis Harvard/Bookings Model, page 44

Common to the recent literature is the acknowledgement that previous measures of capacity such as specified levels of "tons of cargo per linear foot of wharf per year" that could be handled are inadequate as guides to whether a port is operating efficiently or whether capacity should be expanded. For use as a measure of efficiency of the port, the measure assumes some optimum mixture of warehouses, land transport and gives no information about sources of inefficiency. For use as a measure of capacity expansion, the assumption of one "optimum" mix does not seem likely, since costs and benefits would vary among ports and types of ships and one would expect the cost-benefit tradeoff to result in different values of "tons of cargo/linear foot wharf/year." Also, this kind of measure does not contain information about all the costs such as those relating to ship turnaround costs, feeder interface costs and more.

Given a capital budget, selection of an "optimum" port design or terminal investment and short-run technique for a particular port based on economic analysis involves a number of steps:

1. A decision upon the goals or criteria of desirability of the projects to be undertaken. If there is more than one goal, decide upon a procedure of how they might be combined. For a privately operated port, there may be a single goal of profit maximization of the port. For a private port, say a port of an oil industry, the goal may be profit maximization or cost minimization to the oil or other terminal operating company; this may lead to direct consideration of costs of

ships as well as port operations if the terminal operator is also the ship operator, owner or charterer or if he is liable for demurrage type of delay payments.

2. Identification of costs and benefits associated with each goal. For example, a new device for cargo handling may contribute to profits of the port by increasing the share of market (increase in demand) because of better service resulting from decrease in turnaround time and decreased labor costs. The costs would be operating and maintenance as well as capital costs of the new devices.

3. Determination of measures and decision rules to apply to the measure in order to determine if the goal is satisfied. For example, the measure of net present value might be used with the decision rule "invest if the net present value is positive." Applying this to the first example, the net present value would be the difference between the discounted cash flows of increased revenues, plus decreased labor costs, minus maintenance cost and the initial machine cost. Similarly, for the second example the net present value would be the discounted value of increased ship productivity plus decreased labor costs, minus machine maintenance cost, less the initial machine cost.

4. Methods of measuring the costs and benefits to be used in the analysis must next be determined. Two types of questions occur here; one is how to assess values of resources used and benefits gained. The other is to estimate the amount of costs incurred and benefits gained. For many types of

equipment, the market valuation will give an appropriate value of opportunity cost. For the value of increased productivity of ships, it would be necessary to determine how the extra ship time would be used. The second question, in the case of ports, requires an estimate of changes in the quality of service such as decreased waiting time produced as a result of the project, changes in demand and a resulting specification of service and quality provided. The quality of service such as waiting time as a result of design parameters for a fixed demand can be estimated by analytical models like queuing models or by simulation. Demand can be estimated by behavioral or econometric models. The estimated amount of service in each period coupled with the valuation can provide an assessment of costs and benefits for each period under consideration.

5. Alternative projects need to be generated for purposes of evaluation. To do this it is desirable to identify the parameters of the port that control port capacity (amount and quality of service provided) and to characterize their effects on costs and benefits. This has in common with part 4 the estimated total changes in the quality of service. In addition, for the purpose of generating alternative designs it is desirable to identify and quantify relationships between alternative ways of accomplishing the same change (such as a decrease of total time in port by means of changing service rate or changing number of berths) and identify and

quantify impacts of a change in one part of a port on another part (for example, an increase in service rate at a dock would increase flows to warehouses and sheds which might increase costs there). In the case of increased service rate versus number of docks,* we note that both have an effect on total time in port (service time plus waiting time). The costs associated with increasing the service rate are changes in costs of labor, machine or dock space. The costs associated with increasing the number of docks are the expansion costs. The benefits in the first case will result from a decrease in service time and waiting time, and in the second from a decrease in waiting time. The best alternative depends on the costs and any differentiation of the ship operators between costs of time in service and time waiting.

6. Application of decision rules to the cost benefit measures for each of the alternative projects.

The articles reviewed do not explicitly address the question of goals of port projects. The articles that attempt to determine an optimum level of capacity** or optimum design*** parameters based on economic analysis use a cost minimization

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* See Morse.

** DeSalvo-Lave: Supply Demand Equilibrium by Harvard Brookings Model-Berth Occupancy Rate: Gaither & Siden - Minimum Average Cost of Transport.

*** Nicoleau - optimum number of berths.
Plumlee - optimum number of berths.
DeSalvo-Lave - change in service rate of dock.
Aggerschoeu-Karsgaard - service rate (simulation).

goal subject to fixed demand (Plumlee, Nicoleau) or profit maximization with changing demand (DeSalvo-Lave; Agerschoeu).

With the exception of Lave's article, there is no explicit attention to the identification of costs with goals or to the definition of a decision rule. Lave's decision rule is "invest as long as the benefits from reduction in total docking time exceed the annual costs of expansion." This satisfies profit maximization criteria. The Plumlee-Nicoleau articles use a minimum total cost concept to select the optimum number of berths; they find the number of berths that maximize total cost of idle berth time plus ship waiting time. They assumed a fixed demand must be served and their decision is based on minimizing the residual costs of providing this service by a given number of berths. If the costs of idle berths are costs of expansion,* then this rule corresponds to the rule - expand if benefits from reduction in waiting time exceed annual costs of expansion when all possible number of berths are considered. This occurs since the only expansion costs not accounted for in the formula are those corresponding to occupation time of berth by ships which under fixed demand is constant** for all possible number of berths. Therefore, under those assumptions, when the value of waiting time reduction exceeds the annual expansion

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* See comments on Plumlee article in Appendix.

** Note that this would not be true if the service rate were allowed to change and consequently there would not be the correspondence in rules. See also Appendix.

costs, the total cost function will decrease and when waiting time reduction is less than annual expansion costs, the total cost function will increase. Thus, the minimum point is associated with the last point where expansion would occur under the DeSalvo-Lave type rule. However, if demand changes or service rate is changed this correspondence will not hold.

The emphasis in the literature reviewed is on the identification and measurement of the quality of service provided by a new facility. The principal emphasis is on the measurement of delay time. By far the most comprehensive treatment is given by Rallis, who divides the port into sections--sailing routes, harbor channels, quay berths, warehouses, quayside roads--and suggests models for each of these sections by which waiting time and probability of rejection can be calculated. Another effective treatment in estimating delay times is a network analysis as described by Ahrenholz. Since this model includes the entire network, inefficiencies in one section of the port would be reflected in delay times in other sections of the port. Both the analytical method of Rallis and the simulation method of Agerschoeu are useful.* Several other articles (Plumlee, Nicoleau) also attempt to measure delays in a section of a port; however, because of some conflicting assumptions their results are in error.**

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* The analytical methods are especially helpful in understanding tradeoff relationships; the simulation methods in obtaining the effect of all interactions.

** See comments on Plumlee article in Appendix.

Questions of valuation and qualitative relationships among port design and operating variables are explored in only a few cases. For example, in the Davis article, the sensitivity of number of vehicles to turnaround time was noted. Although most of the articles are dealing with the single issue of delay time in our "section" of a port, they take a broad view in identifying the factors that can affect the economic operation of a port. These factors are summarized below.

The literature reviewed in this note suggest the following factors affect the economic operation of a port:

Facility

1. Number and specialization of berths.
2. Ability to move cargo into and out of ships.
3. Ability to move cargo into and out of land transport.
4. Ability to move cargo within port.
5. Ability to store cargo.
6. Port management.

Demand

1. Arrival rate of ships.
2. Cargo distribution/ship
3. Arrival rate of land vehicles
4. Cargo distribution/land vehicles.

The design parameters of the facility could be characterized as:

1. Number and specialization of docks (land transport and sea transport).

2. Number of warehouses and their capacities.

3. Dock area.

4. Loading and unloading rates (equipment and labor).

5. Harbor channel design; ship queue capacity.

6. Network layout (distance between connections).

7. Mechanization of scheduling and reservations.

To progress toward an improved framework and methodology for determination of port capacity and selection of port design, the following problem areas had to be reviewed and studied. Since many ports are in a mixed public-private setting, a study to identify criteria of desirability for various types of ports was desirable. Another area of study was the valuation of costs and benefits, particularly in how to value savings in congestion costs in a setting in which port pricing does not reject these costs. Similarly, we determined measures of quality of service in addition to congestion, such as safety and reliability. An attempt was made to couple valuations models with Rollis congestion measures and examine "optimal" expansion or changes in operating variables under assumptions of profit maximization. Some of the analytical models were extended to cover several port "sections", in an attempt to develop measures of impacts of one section on another (for example, increases in dock service rate on congestion at warehouse). Assuming methods of valuing costs and benefits for each of the port sections, it is possible to couple the analytical "section" models by means of a mathematical programming network model to examine "optimal" expansion or change in operating variables in several sections simultaneously. Systematic use of simulation models could also be used in an attempt to develop qualitative relationships among the impacts of changes in the design variables.

4.2 Cargo Handling Intensity and Utilization of Port Facilities

An attempt was made at deriving measures for cargo handling intensities and utilization of port facilities from currently available official statistics. Such measures are valuable for relative judgement of working condition in different ports, and for annual or monthly monitoring of trends in port development. The measures might furthermore support crude forecasts on port service demand and port performance.

The official statistics used in this report are obtained as follows:

a) Ship Flow: Census; "U.S. Waterborn Foreign Trade, Vessel Entrances and Clearances 1969," (Table FT975)

b) Cargo Flow: Department of the Army, Corps of Engineers; "Waterborn Commerce of the United States 1969" (Treated in the working paper "Trade Flow through Atlantic Ports.")

c) Harbor Facilities: Corps of Engineers - U.S. Army; "Port Services" (Treated in the working paper "Facilities of the U.S. Ports on the Atlantic Seaboard.")

Since the published statistics are aggregations from raw data to support basically different purposes, it is usually difficult to get consistent matches in classification of cargo flow, ship flow and port facilities. This is, of course, a severe problem when attempting to calculate rates, tons of cargo handled per unit of time and berth length (or ship lengrh).

A reasonable match of the statistics is obtained by the following aggregation:

SHIPS	CARGO	WHARFS
General Cargo and Container Ships	Containerized and Non-Containerized	General Purpose and Container Wharfs
Tankers	Liquid Bulk	Oil Handling
Dry Bulk	Dry Bulk	Special Purpose

Some raw statistics may be obtained directly from port authorities, but these will usually be highly incomplete for the calculations mentioned. Detailed studies concerning cargo handling rates, for example, therefore demand special measurements in the ports.

1. Ship Flow

a) Detailed statistics on entrances and clearances, ship by ship, in U.S. Ports are available at the Bureau of the Census in the following files:

AE 350 - Part I: Monthly vessel entrances in alphabetic vessel name arrangement;

AE 350 - Part II: Monthly vessel entrances in Customs District, Port and Manifest Number arrangement;

AE 750 - Part I: Monthly vessel Clearances in alphabetical vessel name arrangement;

AE 750 - Part II: Monthly vessel Clearances in District, Port and Manifest Arrangement.

Since the ships are identified by name in these statistics, further data on ship characteristics may be obtained from classification registers. Printouts of the statistics are expensive, however, and aggregation of the statistics by hand will be very laborious.

b) The total ship flow per year in Foreign Trade, by the number of ships and the accumulated net registered tonnage, is given in Census Table FT 975 - "Vessel Entrances and Clearances." Columns 1, 2, 7 and 8 in Table II, "Ship and Cargo Flow Through U.S. Atlantic Ports - Foreign Trade" are drawn from FT 975. It is important to notice that: "A vessel is reported as entered only at the first port in the United States at which entry is made, regardless of whether cargo is unloaded at that port. A vessel is reported as cleared only at the last port at which clearance is made to a foreign port, regardless of whether cargo is unloaded. Vessels arriving from a U.S. port and proceeding to other ports in the U.S. Customs Area are considered in coastwise movement and are not included in these figures."

c) In Table 49 the data of ship and cargo flow through Port of Boston are given in columns 1 and 2 by number of ships and accumulated DWT respectively. The numbers contain both foreign and domestic trade, and they are drawn from statistics at Boston Port Authority.

2. Time in Harbor

a) Total time in harbor for a ship visit may be found using census' annual tables AE 350 and AE 750 for entrance and clearance respectively. It is, however, not possible to break the statistics into time spent at wharfing or other work time, traveling in and out of harbor, cargo handling, bunkering, etc. Such statistics (that are needed in cargo handling rate calculations) do not seem to be available at the port authorities either, and special studies have to be undertaken if one wants the breakdown.

b) The distribution of total time in harbor for ships entering Port of Boston in 1969 is given in Table 50 and Figures 23 through 26 Statistics for ships spending more than 10 days in harbor are excluded in the diagrams and the calculations of means, since such delays are mainly due to strikes. The statistics are drawn from the day to day registrations at the Boston Port Authority.

3. Cargo Handling Intensity

Columns 1, 4 and 7 in Table 51 "Cargo Handling Intensity" give the sum cargo flow (receipt and shipment) for foreign and coastwise transport (internal and local flow are not included). The statistics are obtained from the working paper "Trade Flow Through Atlantic Ports, Appendix G," by direct summation as follows:

General Cargo = Containerized Cargo + Non-Containerized Cargo

Special Purpose = Dry Bulk Cargo + Special Handling

Oil Handling = Liquid Bulk Cargo

Columns 2, 5 and 8 in Table 51 give the gross berth space and are obtained from tables in Chapter 3.0 "Facilities of U.S. Ports on the Atlantic Seaboard."

Organized as follows:

General Cargo - Containers and General Cargo

Special Purpose - Dry Bulk and Chemicals

Oil Handling - Liquid Bulk

Columns 3, 6, and 9 give the ratio between cargo flow and berth space and may be considered as a measure of "Cargo Handling Intensity" for the different ports.

Column 10 gives the tank capacity for oil handling, and in column 11 the ratio between tank capacity and cargo flow is calculated. This ratio may be considered as a measure for the oil handling intensity relative to the tank capacity.

4. Cargo Flow Relative to Ship Flow in Foreign Trade

Columns 1, 2, 7, and 8 in Table 52 were explained previously. Columns 4 and 10 in Table 52 give the total cargo flow in foreign trade.

In columns 4 and 11 the ratio between cargo flow (in short tons) and ship flow in NRT is calculated.

A crude investigation has shown that for

Tankers: DWT (short tons) = 3 x NRT

Gen. Cargo: DWT (short tons) = 2.7 x NRT

Converting (conservatively) the total ship flow in NRT to DWT (short tons) by 100/3, the percentage cargo flow of ship flow will be as given in columns 6 and 12 of Table 52.

However, the numbers have to be treated with care because of the very special way census has defined the ship flow in foreign trade. Providence shows, for example, an import cargo flow of 133% of the ship DWT flow. This is believed to be caused by ships carrying imported residual oil visiting another U.S. port before unloading in Providence.

The tonnage of foreign and coastwise trade of the major ports on the Atlantic Seaboard are presented by method of handling used in Table 53.

5. Special Investigation for Port of Boston

a) Cargo and Ship Flow

Because of the special structure of the statistics in Table 49 a tentative study was undertaken for the Port of Boston.

In columns 1 and 2 of Table 49the total number of vessels entering the harbor and the accumulated DWT capacity of the ships are given as recorded by the Boston Port Authority.

In column 3 the average tonnage for the visiting ships are calculated and a corresponding judgemental length for that ship size is given in column 4.

The accumulated time spent in harbor and the average time in harbor for a ship are estimated on the basis of the values in Table 50 and given in columns 5 and 6.

In column 7 the accumulated total cargo flow is given (local and internal flow excluded), and in column 8 the percentage of cargo flow of ship flow is calculated.

b) Judgement of Cargo Handling Intensity

In columns 9 and 10 the number and average length of berth units as defined in Chapter 2 are given. (The berth unit distributions are noted in Table 54 .) Returning to Table49 we note that in column 11 the maximum number of "average ships" that can theoretically (no allowance for "handling space") be berthed at the same time is given, and the corresponding available berth capacity in ship-days for one year is noted in column 12.

The percentage of ship-days spent in the harbor are calculated in column 13, and may be considered as a crude relative measure of facility utilization.

Column 14 gives the average tons of cargo handled per ship-day in the harbor.

Columns 15 and 16 give the amount of cargo (in short tons) handled per foot of length of the average dhip and per unit of time (day and year respectively). These numbers are, of course, considerably greater than the numbers calculated per foot length of gross berth space in Table 51 and may be considered as relative measure for cargo handling rates.

The use of average ship length and berth length in these calculations has to be regarded as a somewhat arbitrarily chosen "overall" measure for crude relative comparisons of ports. For the purpose of model building and simulation of the operation of the ports, specific data sampling has to be carried out to obtain such information as cargo handling rates for different types and sizes of ships, carrying different types of cargo in different ways, and loading and unloading at wharfs with different cargo handling gear.

Fig. 22

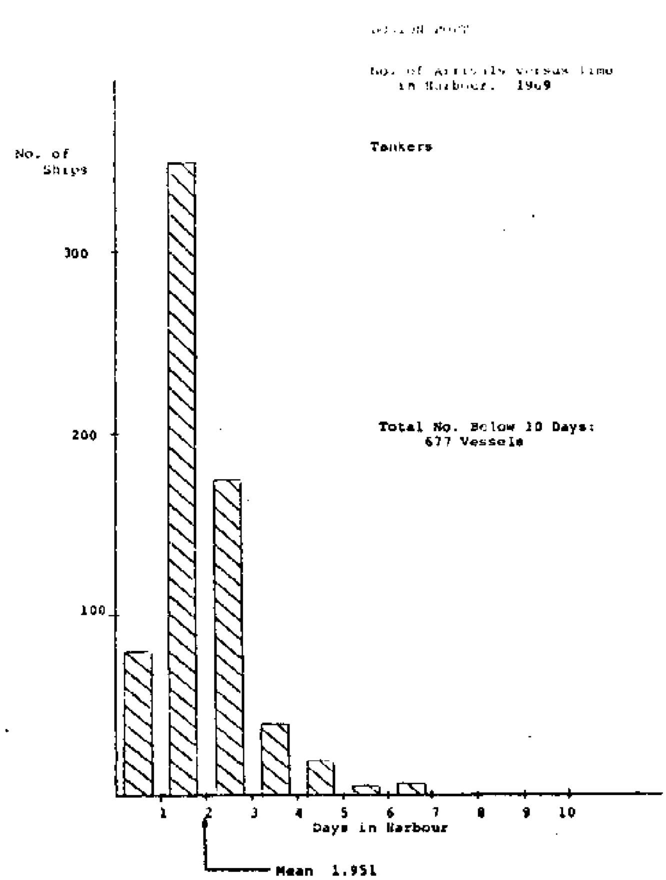


Fig. 24

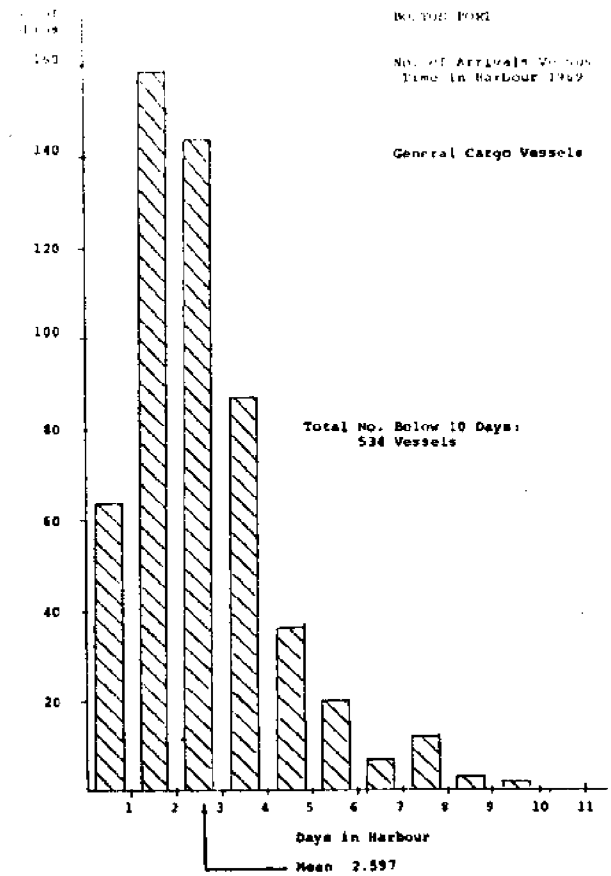


Fig. 23

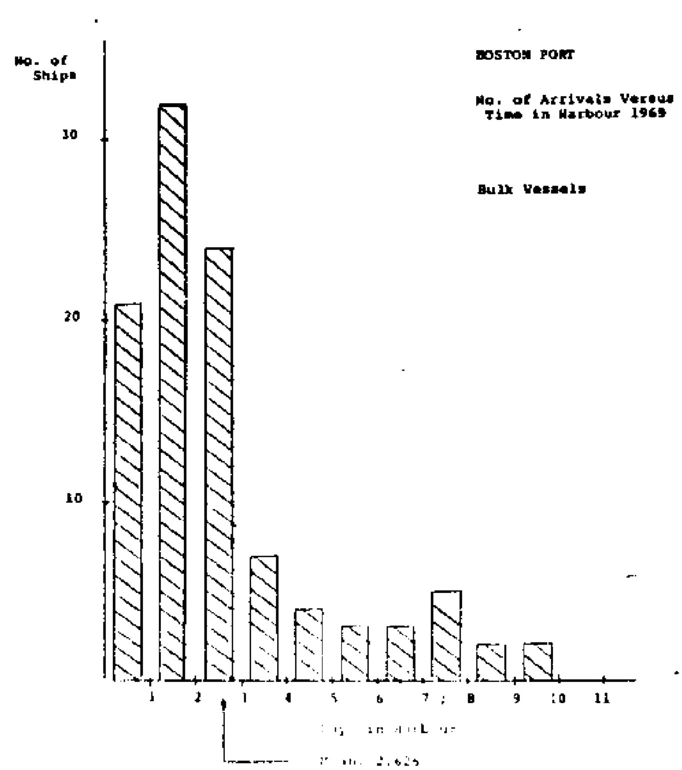
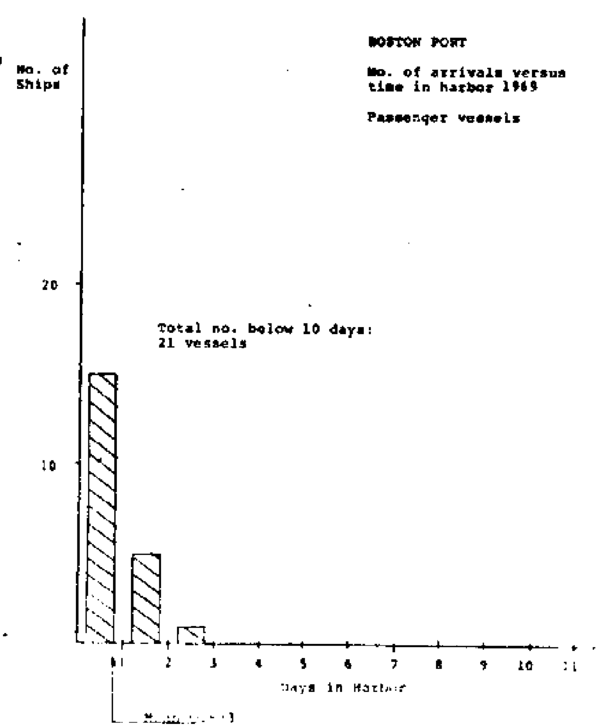


Fig. 25



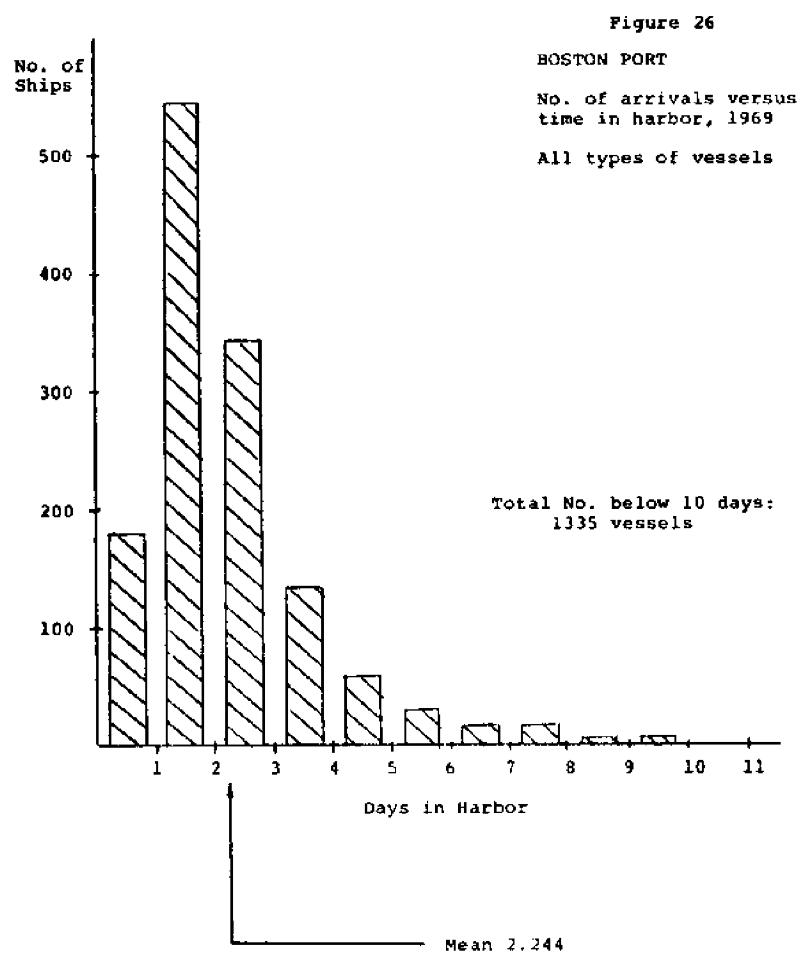


Figure 26
BOSTON PORT
No. of arrivals versus time in harbor, 1969
All types of vessels
No. of Ships
500
400
300
200
100
1 2 3 4 5 6 7 8 9 10 11
Days in Harbor
Total No. below 10 days: 1335 vessels
Mean 2.244

Table 49 SHIP AND CARGOFLOW THROUGH BOSTON PORT 1969

	1 No. of vessels entering the harbor	2 Accumulated tonnage (DW) of visiting ships (long t)	3 Average DW tonnage for visiting ships	4 Estimated length for average ship	5 Accumulated days in harbor for visiting ships	6 Average time in harbor for visiting ships	7 Accumulated cargoflow in and out of harbor (short tons)	8 Percentage cargoflow of ship deadweight flow (both short ton)
Tankers	730	20,680,000	28,300	600'	1,420	1.951	20,821,000	91%
General Cargos	619	6,120,000	9,900	450'	1,610	2.597	673,000	10%
Bulks	124	1,920,000	15,500	500'	320	2.626	1,885,000	88%

	9 No. of berthunits (above 300')	10 Average length of berthunits	11 No. of av. ships to be berthed at same time	12 Available berthing (days*ships) a year	13 Utilization of the berths*	14 Tons cargo handled pr day and pr ship	15 Tons cargo handled pr day and pr foot of ship	16 Tons cargo handled pr year and pr foot of ship
Oil Handling	16	590'	16	5,850	24%	14,800	24.6	9,000
General Cargos	28	760'	47	17,150	9%	418	0.93	340
Special Purpose	10	690'	14	5,120	6%	5,900	11.8	4,300

* Since "time spent in harbor" also contains wharfing, time in and out of harbor, etc., it is not quite correct to label this as berth utilization.

TABLE 50 DISTRIBUTION OF TOTAL TIME SPENT IN HARBOR (DAYS)

BOSTON PORT

Internal	0/1	1/2	2/3	3/4	4/5	5/6	6/7	7/8	8/9	9/10	10/-	SUM	SUM below 10	Mean below 10
Mean of Internal	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5				
Tanker	80	348	175	40	19	6	7	1	0	1	3	680	677	1.951
General Cargo	64	159	144	87	36	20	7	12	3	2	34*	568	534	2.597
Bulk	21	32	25	7	4	3	3	5	2	2	8	111	103	2.626
Passenger	15	5	1	0	0	0	0	0	0	0	1	22	21	0.833
Totals	180	544	344	134	59	29	17	18	5	5	46	1381	1335	2.244

* Mostly due to strikes

Table 51

CARGO HANDLING INTENSITY (PER YEAR)

PURPOSE HARBOR	GENERAL CARGO			SPECIAL PURPOSE			OIL HANDLING				
	Berth Space 10^3ft	Cargo Flow Sh.Ton.	Handling Intensity tom/ft.	Berth Space 10^3ft	Cargo Flow Sh.Tom	Handling Intensity tom/ft.	Berth Space 10^3ft.	Cargo Flow Sh.Tom	Handling Intensity tom/ft.	Tank Capacity Barrels	Handling Intensity Toms/barrels
New York	196.8	16094	81.8	52.1	12463	239.2	51.7	78010	1508.1	99206	0.786
Baltimore	41.5	5259	126.8	48.2	17601	365.3	6.7	6967	1040.9	16664	0.418
Jacksonville	12.7	1309	103.3	2.5	2539	1030.2	4.5	6089	1344.5	6630	0.918
Portland	5.1	48	9.5	2.7	30	11.3	7.0	27149	3895.7	8037	3.378
Boston	21.9	673	30.8	6.1	1885	309.1	10.3	20821	2031.3	17000	1.225
Providence	4.7	98	21.0	1.9	623	327.0	7.9	8693	1097.1	9111	0.954
New Haven	1.6	406	247.6	0.8	938	1202.7	5.4	8971	1651.0	6362	1.4101
Delaware River	55.2	4094	74.2	38.7	15825	409.3	25.9	55845	2157.9	53920	1.036
Hampton Roads	28.9	1765	61.2	13.0	42837	3290.3	5.0	5416	1073.2	5230	1.036
Totals	368.3	29746	80.8	165.8	94742	571.3	124.5	217963	1751.4	222160	0.981

Table 52

SHIP AND CARGO FLOW THROUGH US ATLANTIC PORTS IN 1969 - FOREIGN TRADE

	ENTRANCE - IMPORT						CLEARANCE - EXPORT						
	No. of Vessels	Accum NRT 10^3RT	Average NRT RT	Cargo Flow 10^3SH tons	tons /RT	% Cargo flow of DW flow %	No. of Vessels	Accum NRT 10^3RT	Average NRT RT	Cargo Flow SH.ton	tons /RT	% Cargo flow of DW flow %	& Gen. Cargo Flow of total Cargo Flow
New York	5079	36249	7137	50261	1.387	46	4674	32956	7050	6417	0.195	7	11
Baltimore	1326	10981	8281	19363	1.763	59	1044	7962	7626	5940	0.746	25	13
Jacksonville	897	3731	4159	4495	1.205	40	671	2802	4176	1378	0.492	16	13
Portland	4132	9225	2232	22240	2.411	80	4045	8381	2072	84	0.000	0	0
Boston	1058	4711	4453	9187	1.950	65	894	4924	5509	628	0.139	5	3
Providence	72	584	8111	2328	3.987	133	104	1054	10135	172	0.163	5	1
New Haven	206	1426	6922	2456	1.723	57	222	2266	10207	295	0.130	4	4
Delaware River	1789	19666	10993	53034	2.697	89	1515	16731	11046	2722	0.163	5	5
Hampton Roads	1222	12841	10508	5793	0.451	15	1839	19175	10427	39844	2.078	70	3
Totals	15781	99414	6300	169155	1.702	57	15008	96221	6400	57531	0.598	20	3

Table 53

TONNAGE VALUE FOR FOREIGN AND COASTWISE TRADE OF THE NINE PORTS BY METHOD OF HANDLING

(short tons)

DRY BULK CARGO

Port	Total*	FOREIGN Import	FOREIGN Export	COASTWISE Receipt	COASTWISE Shipment
Portland	29,925	29,925	-	-	-
Boston	1,203,072	180,696	606,925	262,211	153,240
Providence R. & Harbor	375,916	120,011	169,911	187,864	6,140
New Haven Harbor	560,757	220,310	293,797	45,175	1,475
New York	31,289,135	1,716,690	2,070,312	4,048,429	2,172,832
Delaware R.	15,525,407	13,701,034	1,146,173	33,920	135
Baltimore	24,693,708	12,368,490	3,487,921	359,373	71,042
Hampton Roads	46,594,174	1,084,077	38,799,200	215,226	2,544,380
Jacksonville	2,402,039	1,206,595	1,055,997	31,341	97,780

LIQUID BULK CARGO

Port	Total*	FOREIGN Import	FOREIGN Export	COASTWISE Receipt	COASTWISE Shipment
Portland	27,733,102	22,197,393	-	3,921,353	1,030,139
Boston	22,236,422	7,795,018	1,468	11,193,495	1,831,331
Providence R. & Harbor	9,541,035	1,981,520	-	5,995,314	716,234
New Haven Harbor	9,132,941	1,987,683	-	5,958,368	1,025,202
New York	118,391,739	38,235,226	121,016	22,636,928	17,017,001
Delaware R.	73,172,132	36,274,819	433,448	14,317,856	4,819,060
Baltimore	12,201,916	4,258,940	9,227	2,574,007	125,000
Hampton Roads	9,920,985	3,986,385	40,172	1,346,722	43,007
Jacksonville	7,410,001	2,705,538	41,262	3,318,061	24,374

*Total includes internal and local.

Table 53 (continued)

CONTAINERIZED CARGO

Port	Total*	FOREIGN Import	Export	COASTWISE Receipt	Shipment
Portland	27,308	4,988	33	9,676	12,239
Boston	208,495	184,123	13,751	10,206	70
Providence	4,374	2,069	1,811	30	464
New Haven	15,344	926	121	14,297	-
New York	8,095,300	3,640,445	1,350,786	731,254	1,056,716
Delaware R.	890,114	643,157	166,093	15,124	7,144
Baltimore	744,960	272,381	188,330	19,906	121,502
Hampton Roads	613,690	322,635	206,175	1,338	6,364
Jacksonville	534,868	138,424	16,764	139,303	238,491

NON-CONTAINERIZED CARGO

Port	Total*	FOREIGN Import	Export	COASTWISE Receipt	Shipment
Portland	41,485	8,176	19	12,855	160
Boston	488,409	386,466	59,731	18,316	695
Providence	93,605	85,817	271	7,428	-
New Haven	391,993	123,754	450	253,126	13,426
New York	10,835,022	5,027,900	2,531,033	1,080,967	674,517
Delaware R.	3,987,718	1,611,354	915,380	616,977	118,376
Baltimore	4,933,095	1,385,796	2,176,431	187,559	906,771
Hampton Roads	1,407,220	356,224	790,202	34,085	48,057
Jacksonville	916,085	360,506	262,108	45,740	107,864

SPECIAL HANDLING

Port	Total*	FOREIGN Import	Export	COASTWISE Receipt	Shipment
Portland	32	-	32	-	-
Boston	682,348	640,674	265	41,409	-
Providence	139,021	139,021	-	-	-
New Haven	391,993	123,754	450	253,126	-
New York	2,632,809	1,640,445	344,201	383,778	86,459
Delaware R.	1,010,065	804,162	61,055	78,326	33
Baltimore	1,343,539	1,077,883	77,906	157,020	1,139
Hampton Roads	448,309	43,215	8,553	141,839	401
Jacksonville	147,787	83,668	1,921	54,390	7,806

*Total includes internal and local.

Table 54
LENGTH DISTRIBUTION FOR BERTHUNITS IN BOSTON PORT

Interval length	300/400	400/500	500/600	600/700	700/800	800/900	900/1000	1000/1500	1500/2000	SUM	[illegible]
Oil handling No	5	2	3	3	1	0	0	2	0	16	
Length SUM	1750	900	1650	1950	750	0	0	2500	0	9500	590
Special cargo No	2	2	6	6	4	1	2	4	1	28	
Length SUM	700	900	3300	3900	3000	850	1900	5000	1750	21300	760
Special purpose No	1	2	2	0	1	3	0	1	0	10	
Length SUM	350	900	1100	0	750	2550	0	1250	0	6900	690
Total No	8	6	11	9	6	4	2	7	1	54	
Length	2800	2700	6050	5850	4500	3400	1900	8750	1750	37700	680

4.3 Capacity of Atlantic Seaboard Ports

The cargo handling intensity and utilization of Port facilities in U.S. Atlantic ports was discussed in chapter 4.2 in terms of gross commodity flow and facility utilization. The capacity of Atlantic Seaboard Ports will be discussed by dividing the port facilities into:

1) Tanker Terminals
2) Dry Bulk Terminals
3) Container Terminals
4) General Cargo Terminals
5) Specialized Terminals such as:

    LNG

Any estimate of port terminal capacity is obviously subjective. Starting from an assumption of 100% usage by the largest type of vessel capable of being handled at each of the available terminals and transferring cargo at its maximum rate a more realistic measure of terminal capacity estimates based on various assumptions such as average ship size, time between arrivals, average service time, and average cargo handled, for the various types of terminals considered can be developed. An ideal capacity estimate is often based on the following:

A) Tanker, Dry Bulk and Specialized Terminals

   1) Average ship size served by terminal has a deadweight capacity of 80% of the largest vessel that can be accommodated at terminal.

   2) Average terminal works 7 days/week, round the clock

   3) Average loss of 20% of available berth time for ship handling, preparation for cargo transfer, getting ready for sea, etc.

As a result, such terminals are estimated to have an ideal capacity for cargo transfer equal to the normal rate of transfer of a ship of 80% deadweight of the maximum size ship that can be accommodated at the terminal transfering cargo 6,912 hours/ year.

B) <u>General Cargo Terminals</u>

1) Average ship size accommodated at a berth has a deadweight capacity of 60% of the largest ship that can be accommodated at the berth

2) Average port works an average of 80 hour/week

3) Average loss of 10% of berth time for ship handling, preparation to transfer cargo, getting ready for sea, etc.

As a result, such berths are estimated to have a capacity for cargo transfer represented by the normal transfer rate of a ship of 60% deadweight of the maximum size ship that can be accommodated at the berth, working cargo 3600 hours per year.

C) <u>Container Terminals</u>

1) Average ship size accommodated at berth has a deadweight capacity of 75% of the largest vessel that can be accommodated at the berth

2) Average Container terminal works 120 hours/week

3) Average loss of 15% of berth time for ship handling preparation to transfer cargo, getting ready for sea, etc.

As a result such berths are estimated to have a capacity for cargo transfer represented by the normal transfer rate of the terminal of a ship of 75% deadweight capacity of the maximum size ship that can be accommodated at the berth, working cargo 5,309 hours per year.

The above berth capacity measures are obviously subject to criticism as are rigid measures such as general cargo transfer capacities based on berth length, which are commonly used (see Figure 27). For example, it is often assumed, that a general cargo berth capable of handling 550' long ships has a cargo transfer capacity of 150,000 tons per year. Atlantic seaboard port would then provide a capacity for handling in excess of 75 million tons of dry general cargo per year.

Similarly a container berth with a special container gantry may be assumed to operate 4,000 hours and transfer cargo at 20 lifts/hour for an annual transfer of 80,000 containers (20 ft. equivalents). As a second gantry is added to the berth the capacity of the berth is assumed to increase by 70% for a total annual rate of 136,000 containers. Berth Capacity measures such as described above do not consider important factors such as apron width, crane (boom) reach, berth mobile equipment, road or rail access, cargo marshalling or storage area, berth circulation, environmental factors, work rules and many other aspects which greatly effect achievable capacity. Even if an acceptable berth or terminal capacity is determined, we still have the problem of developing a measure of port capacity where the port usually consists of a number of berths of various types, dimensions, and configurations, and operating with different equipment, etc.

A major consideration is really, what constitutes full berth occupancy of ships and a consequent maximum berth utilization and cargo transfer. Considering a single berth we may

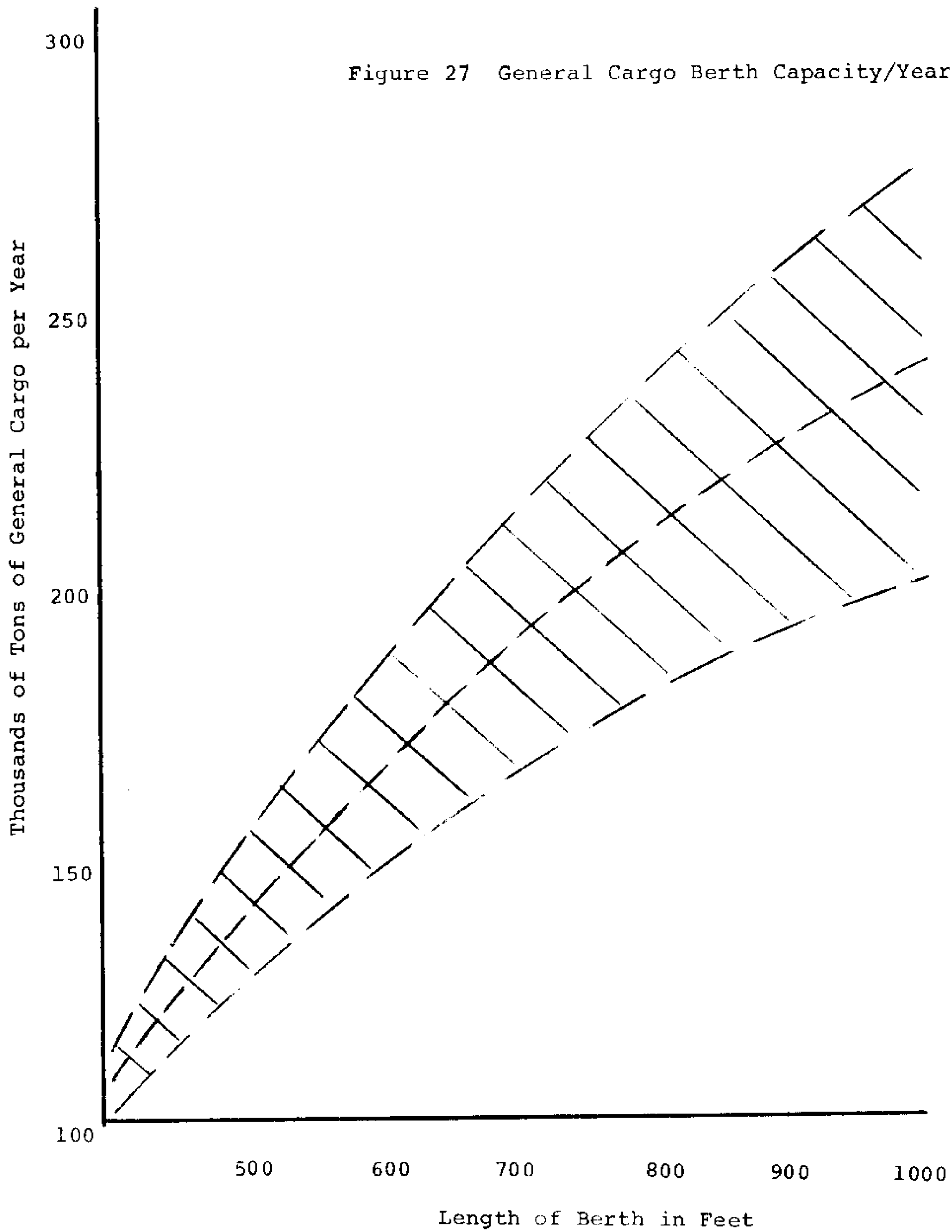


Figure 27 General Cargo Berth Capacity/Year
Thousands of Tons of General Cargo per Year
300
250
200
150
100
500
600
700
800
900
1000
Length of Berth in Feet

define occupancy rate as the ratio of used berth day to available berth days and percentage berth occupancy per year as:

$$\frac{\text{number of ship arrivals/week, month of year} \times 100}{\text{average number of ships served by a berth/day} \times \text{number of berths}}$$

These simple measures assume that ship arrivals per unit time and berth service times of each ship using the berth are known. In that case we could easily determine the ship waiting time corresponding to each level of berth utilization or percentage berth usage. In practice, though, neither are known and therefore more realistic assumptions based on statistical data are made. Poisson frequency distribution of the number of ship arrivals and random arrival times of ships are usual assumptions made. Frequency distribution of service times of general cargo berths is generally taken to be represented by an Erlang distribution. Other types of berths can be taken to conform to similar assumptions. As a result, we usually confront the dilemma of increasing berth utilization with increasing ship waiting time and vice versa. As the competitiveness of a port is a measure of both its costs and turn-around time, these factors are not independent. Total annual ship waiting time can usually be shown to be a function of the product of annual ship arrivals and average service time or total required annual berth service time for a given set of berths. Using the simplifying assumptions of random interarrival, and Erlang service time, distribution ship size, for example, we obtain the percentage waiting time (waiting time/total arrivals x average service time) as a function of berth day demand per berth for

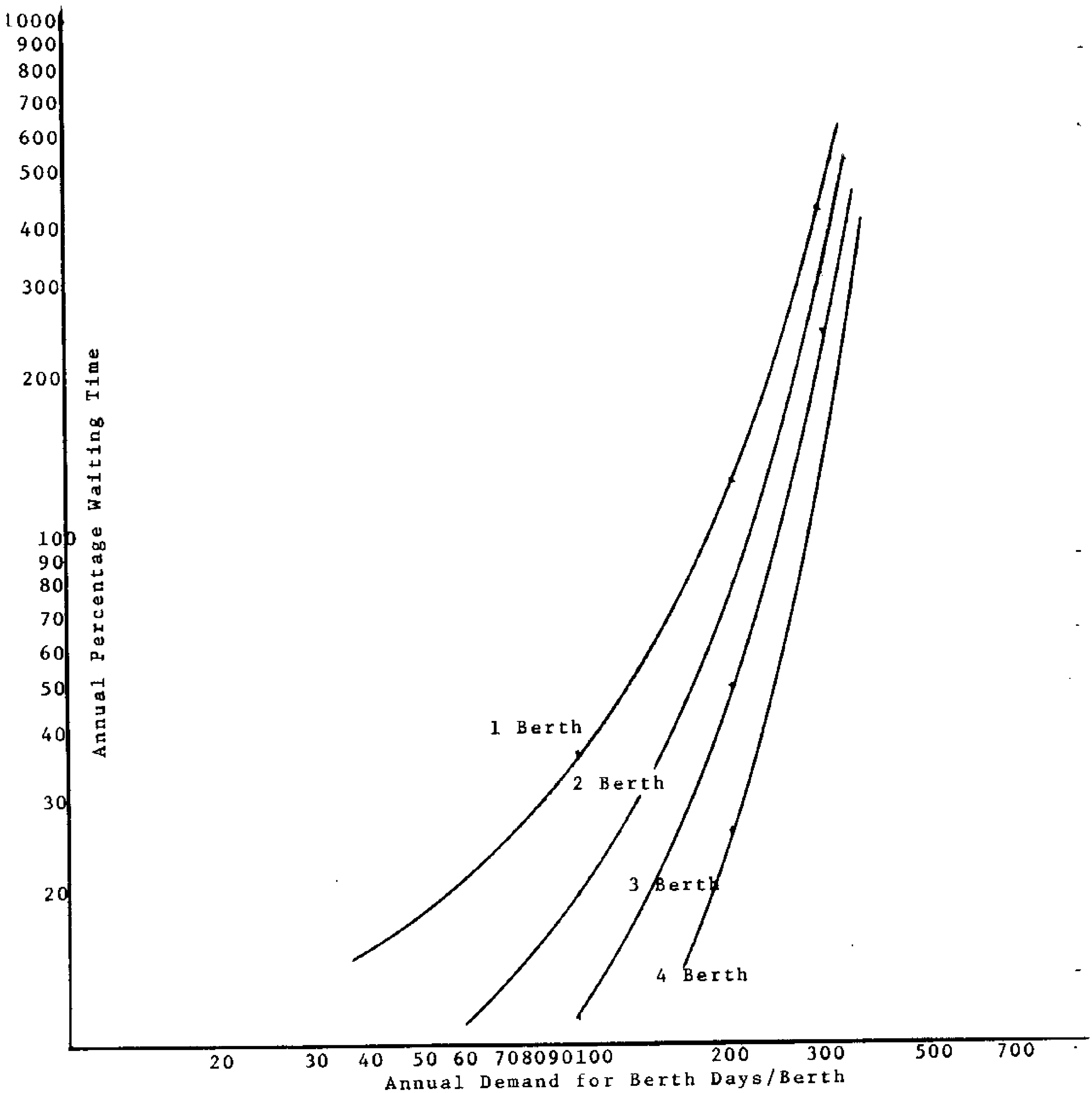


Figure 28 Percentage Waiting Time Loss

various number of berths as shown in Figure 28. It is noted how the percentage of time a ship waits for a berth in relation to berth (service) time required decreases markedly as the number of available berths increases. Another approach to the appraisal of port capacity requirements based on waiting (queuing) is presented in Appendix B.

Using queuing analysis we can obtain an estimate of capacity after translating total ship service time into tons of cargo transfer. This is usually accomplished by assigning cargo transfer rates to berth which include ship and berth characteristics.

Tanker Terminal Capacity

A listing of available Atlantic Coast tanker terminals is presented in Table 55. There are a total of 144 tanker berth available with an average maximum length of tanker that can be accommodated of 718'. The maximum tanker berth draft is available at Portland (41'0") and the average draft at the tanker terminals is about 35'.

Under limiting conditions, tankers of up to 80,000 DWT capacity can be handled by about 40% of the existing crude receiving terminals. The average crude tanker size that can be accommodated at crude landing terminals on the Atlantic seaboard has a capacity of 57,000 DWT. The theoretical transfer capacity of these terminals is about 600 million tons per year. It must be recognized that many of these terminals serve the loading of product for coastwise movements. In fact until 1970 product loadings and landings at Atlantic Coast terminals exceeded crude landings. This is rapidly changing as import crude assumes increasing importance.

It is obvious that the combined capacity of these terminals is ample to satisfy medium term crude and product handling demand as such. The major difficulty is the fact that ship technology has bypassed these terminals which were until 1960 the pride of this nation and the envy of the world. Until that time we were the only major oil consumer capable of utilizing the supertankers (45,000-57,000 DWT) of that period. While many of the industrial nations of the world have since leapfrogged our tanker terminal developments and are now capable of accommodating much larger tankers, the U.S. has not made any major improvements in tanker terminals of similar significance. The increasing dependence of the U.S. on crude imports, the fact that most of these imports should be landed on the Atlantic coast, the increasing difficulty of obtaining sufficient medium size tanker tonnage, and the large economic penalty of importing crude in tankers of less than 80,000 DWT have an important effect on the sufficiency of tanker terminal capacity. While the gross capacity appears adequate (though not always balanced) the economic terminal capacity is grossly deficient.

Table 55

Tanker Terminals on the U. S. Atlantic Coast *

Port Terminal	Port Authority Operating Company	No. of Berths	Max. size Length O.A. (Beam)	Draught
ALBANY	Albany Port District Com.			
Socony Dock	Socony Mobil Oil Co. Ltd.	2	740'	25'6"
Atlantic Dock	Atlantic Refining Co.Ltd.	2	600'	25'6"
BALTIMORE	Maryland Port Authority			
American Oil, Curtis Bay Terminal	American Oil Co.	2	600'	31'0"
Hess Oil Terminal	Hess Oil & Chemical Co/Phillips Petroleum Co/Tidewater Oil Co.	1	630'	35'0"
Sinclair-Texaco Terminal	Texaco Inc/Sinclair Refining Co.	1	650'	33'0"
American Oil, Wagner's Point	American Oil Co.	1	610'	32'0"
Shell Oil Terminal	Shell Oil Co.	2	700'	23'0" 35'0"
Humble Oil Terminal	Humble Oil & Refining Co.	2	715'	35'0" 37'0"
Crown Central Oil Pier	Crown Central Petroleum Corp.	1	600'	35'0"
C. Hoffberger & Co. Pier	Gulf Oil Co.	1	700'	35'0"
Canton Pier No. 1	Ashland Oil and Refining Co.	1	600'	31'0"
Continential Oil Terminal	Continental Oil Co/ American Bitumuls & Asphalt Co/Cities Services Oil Co/ Mobil Oil Co/Tenneco Oil Co.	1 finger 1 marginal	700' 580'	34'0" 32'0"
BOSTON	Massachusetts Port Authority			
East Boston	State Fuel Co.	1	610'	30'0"
Chelsea	Texaco Inc.	1	700'	35'0"
	Mobil Oil Co.	1	850'	30'0"
	Jenney Mfg Co.	1	700'	32'0"
	American Oil Co.	1	660'	33'0"
	Gulf Oil Corp.	1	860'	31'0"
Revere	Tide-Water-Atlantic	1	800'	35'0"
	Union Oil Co.	1	1,200'	33'0"
	Tenneco Oil Co.	1	630'	30'0"
Everett	Humble Oil Co.	1	800'	36'0"
South Boston	Boston Edison Co.	1	575'	30'0"
	White Fuel Corp.	1	1,000'	38'0"
Quincy	Quincy Oil Co.	1	600'	32'0"
	Mobil Oil Co.	1	850'	36'0"

*Ref. Oil and Gas Journal, Oct. 1971 - Corps of Engineers Reports

Table 55 Continued

Weymouth	Edison Electric Co.	1	630'	31'0"
Braintree	Cities Service Oil Co.	1	700'	34'0"
CHARLESTON				
Shell Berth	Shell Oil Co.	1	575'	32'0"
Gulf O				
Gulf Oil Deck	Gulf Oil Corp.	1	625'	28'0"
	Sinclair Refining Co.	1	661'	34'1"
	Humble Oil Co.	1	270'	35'0"
	Phillips Petroleum Co.	1	200'	35'0"
	Texaco Oil Co.	1	705'	31'10"
	Hewitt Oil Co.	1	235'	35'0"
	Hess Oil Co.	1	60'	35'0"
MIAMI	Seaport Dept. Dade County, Miama			
Belcher Oil Dock	Belcher Oil Co.	1	528'	30'0"
JACKSONVILLE	Jacksonville Port Authority	1	680'	34'0"
Shell Dock	Shell Oil Co.	1	680'	34'0"
Gulf Dock	Gulf Oil Cpr.	1	644'	34'0"
Standard Oil Dock	Standard Oil Kentucky Co.	1	615'	31'0"
Phillips	Phillips Petroleum Co.	1	680'	34'0"
Sinclair Dock	Sinclair Co.	1	700'	36'0"
Texaco Dock	Texaco, Inc.	1	600'	31'0"
Hess Dock	Hess Fuel Oil Co.	1	no limit	34'0"
Commodores Point Term.	Commodores Point Terminal Co.	1	661'	34'0"
NEW YORK	Port of New York Authority			
Bayonne, NJ	Bayonne Industries Inc.	3	630'	32'0"
Elizabeth, NJ	Crown Central Petroleum Corp.	1	650'	30'0"
Astoria, NY	Greater New York Terminal Inc.	2	732'	31'6"
Newark, NJ	The Atlantic Refining Co.	1	750'	31'0"
Newark, NJ	Atlantic Coast Terminal Inc.	1	628'	32'0"
Newark, NJ	Coastal Oil Co.	1	600'	32'0"
Bronx, NY	Oceana Terminal Corp.	3	660'	34'0"
Port Socony, NY	Mobil Oil Co. Inc.	2	650'	30'0"
Bayonne, NJ	Ross Oil Terminal	1	870'	34'0"
Sewaren, NJ	Royal Petroleum Corp.	1	675'	34'0"
Sewaren, NJ	Shell Oil Co.	1	575'	34'0"
Jersey City, NJ	Tankport Terminals, Inc.	2	900'	34'0"

Table 55 Continued

Hastings-on-Hudson, NY	Tappan Tanker Terminal Inc.	1	1,200'	35'0"
Brooklyn, NY	Whale Oil Co. Inc.	2	600'	36'0"
NORFOLK	Norfolk Port and Industrial Authority			
Newport News	Socony Mobil Oil Co. Inc.	1	650'	35'0"
	Gulf Oil Corp.	1	700'	30'0"
PHILADELPHIA	Delaware River Port Authority			
Paulsboro	Paterson Oil Terminals, Inc.	1	700'	33'0"
	Socony Mobil Oil Co.Inc.	1	750'	32'0"
Marcus Hook	Port Authority	1	650'	33'0"
Delaware City	Port Authority	1	660'	34'0"
PORT ARTHUR	Gulf Oil Corp.	6	750'	36'0"
	Texas Co.	3	700'	35'0"
Atreco	Atlantic Pipe-Line Co.	3	700'	35'0"
PORT EVERGLADES	Port Everglades Authority (Five additiona under construction)	18	845'	37'0"
PORTLAND, ME.	Maine Port Authority			
Pier #1	Portland Pipe-Line Corp.	2	675'	35'0"
Pier #2	Portland Pipe-Line Corp.	2	775'	41'0"
American Oil Pier	American Oil Co.	1	600'	30'0"
Chevron Oil Pier	Chevron Oil	1	600'	32'0"
Esso Pier	Humble Oil and Refining Co.	1	550'	30'0"
Gulf Pier	Gulf Oil Corp.	1	600'	32'0"
Shell Pier	Shell Oil Co.	1	650'	32'0"
Socony Pier	Socony Mobil Oil Co.Inc.	1	750'	35'0"
American Oil Pier	American Oil Co.	1	600'	30'0"
Chevron Oil Pier	Chevron Oil	1	600'	32'0"
Esso Pier	Humble Oil and Refining Co.	1	550'	30'0"
Gulf Pier	Gulf Oil Corp.	1	600'	32'0"
Shell Pier	Shell Oil Co.	1	650'	32'0"
Socony Pier	Socony Mobil Oil Co.Inc.	1	750'	35'0"
Tidewater Pier	Tidewater Oil Co.	1	560'	28'0"
Texaco Pier	Texaco Inc.	1	560'	30'0"
PORTSMOUTH, NH	State Port Authority			
Mobil Terminal	Mobil Oil Co.	1	650'	35'0"

Table 55 Continued

C.H. Sprague & Sons	C.H. Sprague & Sons	1	650'	35'0"
Atlantic Terminal	Atlantic Terminal Sales Corp.	1	650'	35'0"
Humble Oil & Refining Co.	Humble Oil & Refining Co.	1	650'	35'0"
New England Berth Gulf Oil & Refining Co.	New England Tank Ind. Inc.	1	650'	35'0"
PROVIDENCE, RI	Department of Public Works			
Socony Terminal	Socony Mobil Oil Co. Inc.	1	600'	34'0"*
WILMINGTON, NC	North Carolina State Ports Authority			
Shell Oil Dock	Shell Oil Co. Atlantic Refining Co.	1	630'	33'0"
Esso Standard Div. of Humble Oil & Refining Co. Dock	Esso Standard, Div. of Humble Oil & Refining Co.	1	725'	35'0"
American Oil Co. Dock	Americal Oil Co. Mobil Oil Co.	1	650'	32'0"
Texaco Inc. Dock	Texaco Inc. Phillips Petroleum Co.	1	630'	33'0"
Chevron Asphalt Co. Dock	Chevron Asphalt Co.	1	600'	32'0"
Hess Oil & Chemical Co Dock	Hess Oil & Chemical Co. Crown Central Petroleum Corp.	1	630'	32'0"
Cape Fear Terminal Dock	Pure Oil Co. Gulf Oip Corp. Sinclair Refining Co. Marathon Oil Co.	1	680'	33'0"
Carolina Netrogen Corp. Dock	Carolina Nitrogen Corp.	1	510'	24'0"
Wilmington Chemical Terminal Dock	Wilmington Chemical Terminal Inc. Wilmington Sulphur Terminal	1	614'	38'0"
Atlantic Coast Line Railroad Dock	Atlantic Coast Line Rail-Road Co.	1	630'	25'0"

* Reference "Oil and Gas Journal 1972"

Container Terminal Capacity

Although the first specialized container terminal was established just over 10 years ago, we now (1971) have over 154 container terminal berths on the U.S. Atlantic Coast, as listed in Table 56.

Many of these berths are equipped with special container gantry cranes (64) and most have large open container storage or marshalling areas. (Table 57) The average container storage area per berth is 28.8 acres. Using an average of 4,000 working hours and 10 container turns per hour average the total Atlantic container terminal capacity is theoretically equal to over 5 million containers (20' equivalents) per year. To derive an actual capacity which includes consideration of lost time, ship handling, etc. an estimate of 3.2 million containers per year was derived. This is obviously far in excess of projected medium term requirements.

On the other hand, there appears to be a gross imbalance in the use of the existing capacity. Using the above noted capacity measure, container terminal berth utilization on the Atlantic coast varies from a high of 82% to a low of less than 10%. Total Atlantic imports and exports in 1972 were less than 1.5 million containers (20' equivalent) and the 3.2 million mark is not expected to be reached before 1988.

Table 56

Container Terminals on the U. S. Atlantic Coasts *

Port	Container Terminal	No. Berths	Container Cranes	Area	Users
SOUTH ATLANTIC					
Miami	Dodge Island Seaport	10	1 70-ton mobile crane	acres 275	Public
Port Everglades	Sea-Land Terminal	1		11	Sea-Land
Jacksonville	Sea-Land Terminal Talleyrand Terminal Blount Island Terminal	2 6 2	1 27.5 ton Paceco Mobile cranes 1 45-ton ctr crane	NA 17	Sea-Land Public Public
Savannah	Container Central	2	1 45-ton Kocks	20	Public
Charleston	Columbus St. Terminal Pier (8) North Charleston Terminal	2 2	1 ctr crane 2 50-ton gantries 1 40-ton Starporter 2 50-ton gantries	NA 25	Sea-Land U. S. Lines Seatrain
Wilmington, N. C.	General cargo berths	9	2 45-ton gantries 1 75-ton gantry	NA	U. S. Lines, "K" Line, Barber
HAMPTON ROADS					
Norfolk	Norfolk International Terminals	9	5 Paceco cranes	360	U. S.,Seatrain, AEIL, Dart, Port Lines, Hapag-Lloyd, Belgian, ACT
Portsmouth	Portsmouth Marine Terminal	3	5 Paceco ctr cranes	150	ACL, Sea-Land
Newport News	Newport News Terminal (Pier B) Newport News Terminal (Pier C)	3 1+	1 50-ton mobile LeTourneau 1 Paceco crane	7.7 NA	 NA
Baltimore	Sea-Land Terminal (Canton Sea-Girt Terminal) Dundalk Marine Terminal	1 12	1 27.5-ton Paceco 8 ctr cranes	17.5 540	Sea-Land US Lines, Hapag-Lloyd, Mooremac, ACL, Seatrain & public
	Locust Point Marine Terminal	3	2 75-ton "revolving cranes"	50	Public
Wilmington, Del.	Wilmington Marine Terminals	NA	NA	NA	NA
Philadelphia	Sea-Land Terminal (Delaware River Terminal - Pier 179) Tioga Marine Terminal Packer Ave. Terminal	1 6 7	1 27.5-ton Paceco 1 55-ton Kocks 1 55-ton Kocks 1 mobile LeTourneau	NA 90 45	Sea-Land & Mooremac Public Public

*Ref. Corps of Engineers and The Impact of Maritime Containerization on the U.S. Transportation System - Manalytics, Feb. 1972.

Table 56 Continued

Staten Island	Stapleton Container Facility	5	1 50-ton Peiner 2 barge ctr cranes	55	Transamerica Trailer Transport & public
	Howland Hook Freight Distribution Center	5	4 40-ton IHI cranes	600	public
Brooklyn	Northeast Marine Ctr Terminal	2	2 ctr cranes	75	
	Columbia St. Ctr Terminal	8	NA	40	
	Bush Terminals (Piers 3 & 4 LASH terminal	NA 2 est.	NA	100	Universal Term. & Steve.Corp.Prudential-Grace
Port Newark	Port Newark	11	8 ctr cranes	381	UT&S, Meyer Line K Lines, US Line APL, Prud-Grace
Elizabeth	Elizabeth Port Authority Marine Terminal	24	NA	919	
	Sea-Land Terminal	6	4 25-ton Paceco	111	Sea-Land
	Ctr Terminals N.Y., Inc.	6	2 Paceco cranes	158	ACL & Mooremac
	Int'l Terminal Op. Co.	3	4 Starporter cranes	85	US Lines, Hapag-Lloyd, Dart & public
Weehawken, N.J.	Port Seatrain	2	3 45-ton Herbert Morris "sliding cantilever" ctr cranes	8	Seatrain
Edgewater, N.J.	Seatrain Terminal	2	1 ctr crane	12.5	Seatrain
Port Jersey, N.J.	Global Container Services	2	2 45-ton Star-porters	62	Dart, Fabre & Columbus Lines (owners of Global)
NORTH ATLANTIC					
Boston	Castle Island Terminal	1	1 27.5-ton Paceco	13	Sea-Land
	Mystic Public Container Pier	3	1 50-ton Hitachi 1 70-ton Hitachi	45	Public

* THE IMPACT OF MARITIME CONTAINERIZATION ON THE UNITED STATES TRANSPORTATION SYSTEM. Volume 2 Manalytics, Incorporated, San Francisco, Calif. February 1972

Table 57

Container Berths and Capacity on
U. S. Atlantic Coast
(1975)

	Number of Berths	Number of Container Cranes (Total Cranes)	Storage Area (Acres)	Capacity in * Number of Lifts per 4000 hr year
North Atlantic	127	49 (63)	3980	4,560,000
South Atlantic	27	15 (16)	527	480,000
Total	154	64 (79)	4507	5,040,000

* (20 lifts or 10 container turns per hour)

Dry Bulk Terminal Capacity

The majority of dry bulk terminals are specialized and proprietary. The total number of dry bulk terminals in the 9 major Atlantic ports is 127 which break down as follows:

	Number	Average Length	Average Draft
Grain	8	850'	33'0"
Sugar	12	550'	31'6"
Paper	4	550'	32'0"
Lumber	8	530'	26'0"
Copper	7	520'	32'0"
Gypsum	12	525'	30'0"
Cement	3	480'	27'6"
Coal	20	920'	32'6"
Misc. Dry Bulk	53	720'	32'6"
Total	127	706'	32'4"

Two grain and five coal terminals have berth with depth in excess of 40'. Similarly six miscellaneous dry bulk terminals can accommodate 40' plus vessels. The capacity of dry bulk terminals could not be estimated, as details of cargo transfer devices and therefore, transfer rates were not available. Using industry averages and a 5,400 hour working year, we obtain the rough approximations presented in Table 58.

TABLE 58

Dry Bulk Terminal Capacity

Commodity	No.	Available hours/year	Average Available Transfer Rate per terminal per hour	Total Annual Transfer Capacity
Grain	8	5,400	1,200	51,840,000
Sugar	12	5,400	1,000	64,800,000
Paper	4	5,400	400	8,640,000
Lumber	8	5,400	200	8,640,000
Copper	7	5,400	250	9,450,000
Gypsum	12	5,400	1,600	103,680,000
Cement	3	5,400	1,500	24,300,000
Coal	20	5,400	3,000	324,000,000
Misc. Dry Bulk	53	5,400	500	143,100,000
Total	127	-----	-----	1,321,650,000

General Cargo Terminals

The number of general cargo berths available in the nine major Atlantic ports is in excess of 400. Most of these berths offer depths of 30' - 35' and lengths which average 550' - 700'. With very few exceptions these general cargo berths are not equipped with shore based cranes, but rely on shipboard cargo transfer equipment. A majority of available general cargo berths are obsolete also because of insufficient apron width, effective circulation or excess (for use of heavy modern equipment) and adequate, efficient storage sheds and open storage areas.

Although the majority of these berths are marginal piers, a significant number of narrow finger piers still serve as general cargo berths. The average amount of general cargo handler per berth was about 73,000 short tons in 1970. This is about 48% of the conventionally assumed capacity of a general cargo berth (150,000 s.t. per year). This capacity is for berths averaging 550' in length. The average length of berths in Atlantic ports is over 650' and the resulting capacity per berth is, therefore, estimated at 180,000 s.t. per year, or a total capacity of 73 million s.t. per year. The resulting utilization achieved is then about 41%.

An alternative approach is to derive a capacity per unit length of berth. (see Table 51). Using the throughput achieved by Baltimore, for example, of 126.8 tons/ft. as a norm, the total general cargo capacity of Atlantic ports is 46.7 million tons versus 29.7 million tons actually handled.

If efficient European general cargo berths (with shore cranes) are considered, data indicates that berth capacities can be expressed as:

[250,000 + 500 (Length in ft. - 550')] tons/year

If this capacity measure is used for comparison, we find that total U. S. Atlantic port general cargo berth capacity is about 126 million tons/year and utilization achieved only 24%.

Specialized Terminals

There are a significant number of specialized bulk terminals in Atlantic ports. All of these are proprietary berths. They include 28 berths for chemical carriers and 5 berths for liquified natural gas or other gas such as LNG, PLG, Methane, etc. The capacity of these terminals or berths could not be established because of the complexity and diversity of the transfer facilities, most of which form an integral part of chemical and/or gas storage and distribution plants. Most of these terminals accommodate ships with drafts of 27' to 33'. Six chemical tanker berths and two LNG tanker berths are designed for ships with drafts of up to 37'.

5.0 PORT ANALYSIS

5.1 Introduction

The functions of a port are usually to transfer goods between seaborne and inland transport modes. The criteria or objective in port design and operation may be to

a. Maximize flow through the port.

b. Maximize revenue from port operations.

c. Maximize profit from port operations.

d. Maximize the capital recovery factor.

e. Achieve required capacity at minimal cost.

f. Achieve minimum total transportation cost by optimum mix of port and transport system components.

g. Minimize capital investment per unit capacity for a given flow.

h. Present value of future benefits.

i. Other

To achieve a given defined objective or multi-objective, we usually analyze the problem of port design, investment, and operation to determine the required policy. This includes derivation of methods for the efficient use and allocation of investment, facilities, labor and equipment, and the introduction of incentives for increased productivity. Port analysis is usually concerned with a nonstatic situation in which consideration is given to the relation between growth over-time in shipping or cargo flow, and facilities or resources to achieve a dynamic optimum

A port is an operational system in which methods of operations research are effectively applied for decision-making. Basically, in structuring a port model or analysis, port operations are broken down into constituent parts and then expressed in mathematical notation in such a way that the capacity of the port or its component parts can be related to the cost of its provision or operation. The effect on the cost of ship and cargo time are obviously also important parameters.

Analysis can also be performed to determine a static optimum which is usually defined as the "Best Use of Existing Facilities" by planned investments or cost allocations for optimum operations in relation to a steady traffic and/or cargo flow.

As a starting point in the construction of a model of a seaport, the following must be determined to derive the definition of relevant inputs:

1. What are the important characteristics of a seaport and its environment?

2. Where is it most convenient to draw the boundary between the port and its environment? (i.e., what functions should be considered part of the port, and what considered exogenous?)

3. What quantities or processes are inputs, and what are outputs to the chosen "Control Volume"?

4. What is the causal structure relating outputs to inputs within the control volume?

The operation of a real seaport and the interaction with its environment are in reality highly complex phenomena, involving the interrelationship of many complicated processes. An attempt has therefore been made to break the system down into major "building blocks" representing conceptually distinct facets of port operation. The structure within these blocks may then be examined in more detail.

The breakdown is shown schematically in Figure 29. The character of the port is represented by three sorts of information:

1. Physical state (configuration of facilities, utilization, etc.).

2. Day-to-day operating schedules (priorities for serving different ships, pricing policy for seaport services, etc.).

3. Financial position (income, expenditure, debt, capital investment).

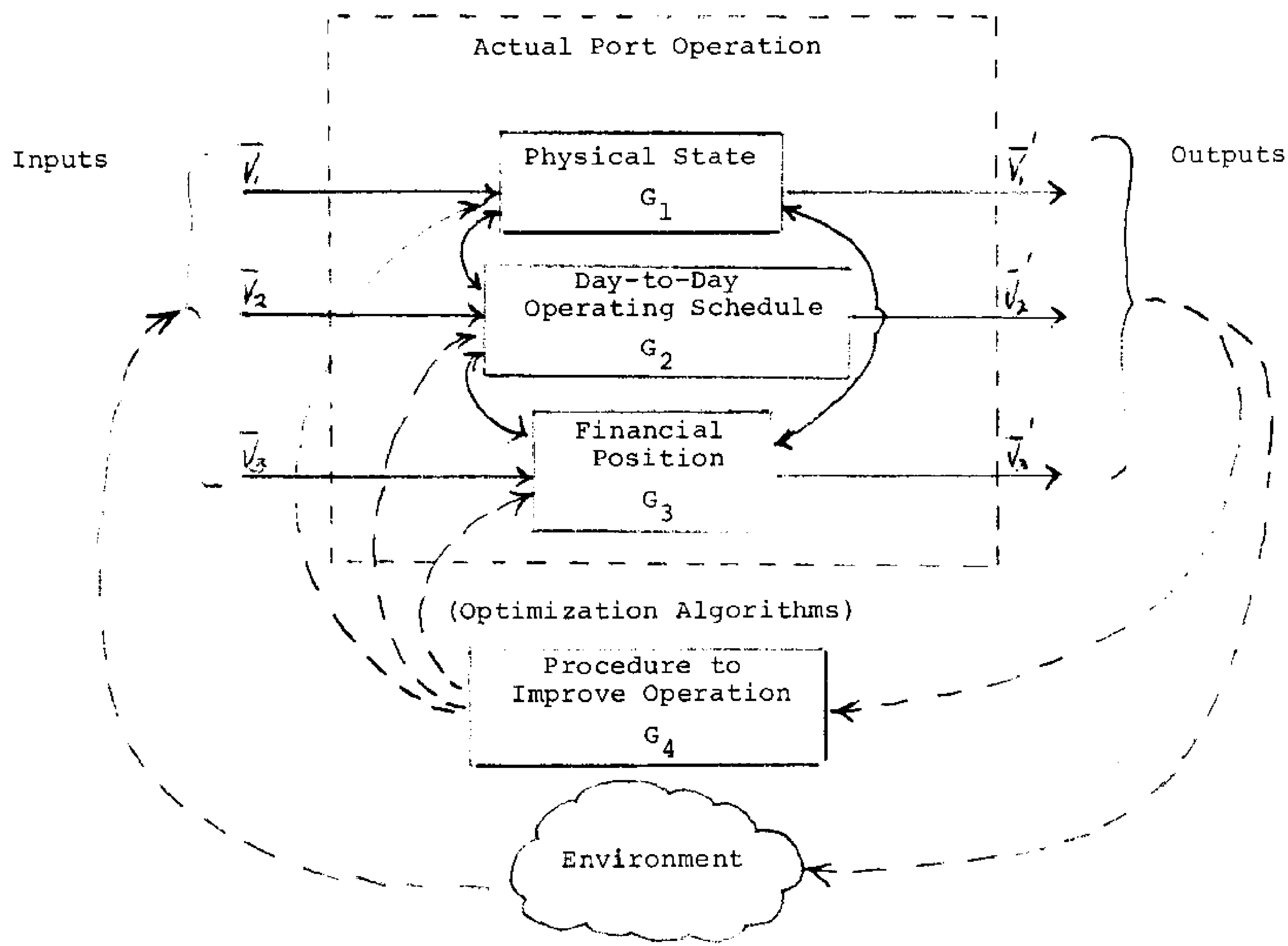
Each of these may be considered as a "black box", with a state which varies over time, inputs, and output. The inputs include the state of the other black boxes. The details of the actual physical objects and information lying within each box are discussed in more detail in the following section.

In addition to the three blocks representing the actual seaport operation, there are two nested outer "control" or feedback loops.

One of these represents the effects of the seaport management who react to whatever information they can get about the state and inputs of the seaport, and make changes in the structure of the system (configuration within the boxes) in response to these inputs. Typical changes would be additional berth space or shed facilities, a change in charges made for port services, borrowing capital or paying off outstanding debts, etc.

A larger loop surrounds this, and represents the interaction of the seaport with its environment. The demand for port facilities depends in part upon the quality and quantity of service which the port offers. For the time being these influences will be considered exogenous, and the outer loop left "disconnected", because it is felt that the first priority is a simulation of the port itself.

Figure 29 Over-All Structure of a Seaport System



1. The Physical State of the System - The box labeled G_1 in Figure 39 represents material flow within the port, and the effects upon this flow of the facilities available to process the flow.

Inputs to Block (V_1) - The inputs to this block are cargo, which may be classified as follows:

- Waterborne
  - Ships
    - Coastal Traffic
      - Ships
      - Barges
    - Deep-water Traffic
      - Tightly scheduled cargo ships
      - Tramps with flexible schedules
- Cargo Types
  - Deck cargo
  - Bulk cargo
  - Containerized goods
  - Small goods
- Land-borne
  - Railway trains
  - Trucks
  - Pipelines

Elements within the Block (G_1) - The enumeration of physical facilities is fairly straightforward; goods progress through it sequentially in either direction.

- Approach Channels
- Anchorage area
- Berth facilities
  - Quay space
  - Cranes, forklift trucks
  - Pumps, conveyor belts
- Transit sheds
- Warehouse
- Shipper-owned storage areas
- Land transport interface (loading bays)
- Land access routes
  - Railyards and feederlines
  - Roads
- Intra-port transportation of goods
  - Trucks, barges, pipelines, etc.

Goods progress through these various areas at rates which depend upon the relative usage of the respective facilities, pressure from management to expedite certain processes, etc.

Outputs of Dock ($\bar{V}_1'$) - The outputs are qualitatively the same as the input; goods flow out into both land and sea carriers.

2. Day-to-Day Scheduling Operations (G_2)

Certain specified policies are followed by seaport management regarding priorities of servicing different ships, prices charged for port services, and the like. These policies direct specific actions on the basis of detailed information regarding current activity of the port:

Input to Operating Schedules ($\bar{V}_2$) - Three sorts of information may be obtained:

- Arrivals of ships and land transport
  - Quantities of goods to be transferred
  - Type of cargo
    - Cost or revenue resulting
- Expected future demand (ship arrivals); corrupted by noise due to inadequate information and uncertainty about the future
- Present utilization of all port facilities; corrupted by noise, time lag, and filtering

Scheduling Process (G_2) - This has not yet been characterized; it may depend largely on the details of an individual port.

Output of Scheduler ($\bar{V}_2'$) - The output of the scheduler is simply the order in which various cargo transfer operations are performed when what facilities are allowed to saturate, and who is kept waiting how long.

3. Financial Structure (G_3)

The financial structure of the port is characterized by income, financial policy, and expenditure, and may be considered in terms of dollar flows.

Income ($\bar{V}_3$) - There are three categories of income:

- Outside investment or loans
- Investment by port users (construction of user-controlled facilities, etc.)
- Operating revenues

Financial Policy (Dollar Flow Network) (G_3) - The financial policy has not yet been detailed. Presumably a number of "profit centers" exist, i.e., departments which attempt to maximize profit resulting from their own particular activity; and their individual policies will be a combination of their own profit picture and the influence of port management attempting to coordinate their activities.

Expenditures ($\bar{V}_3'$) - Expenditure falls into the usual categories:

- Running costs for services provided
- Maintenance and depreciation
- New equipment and facilities
- Debt interest and repayment on principal

4. Long-Range Policy Design and Optimization (G_4)

Outside the physical structure of the port, and comprising a feedback loop around it, are the attempts of port management to improve system performance over a period of time. Based on their judgment and whatever knowledge is available about the state of the port and its environment, they must make specific decisions regarding expansion of facilities, charging policies, and so on. In other words, they must change the structure of the boxes G_1, G_2, G_3, and G_4 in order to best match the seaport to the present characteristics of the environment and its demand on the seaport's services. This is normally done on the basis of experience and judgment. It is hoped that the present study will result in the development of dynamic programming algorithms to perform some of these functions in optimal fashion.

Information Input for Optimization - Information used in the optimization process falls into three categories:

- The state of the system: effectiveness, value and extent of facilities
  - Average utilization of various facilities
  - Scheduling policies
  - Charging policies
  - Financial status: debt, income
- The state of the environment
  - Current demand for various types of service
  - Forecast future demand
  - Estimated effects of modifications to the port upon future demand
- Optimization criteria
  - Profit
  - Cargo throughput
  - "Social good"
  - Cost of improvements to port
  - Availability and cost of capital for improvements

Outputs of Optimization - The output of the optimization procedure will be specific changes in the structure (physical or policy) of the port:

- Physical configuration
  - Capital improvement, in quantity or technological level of facilities
  - Retirement of obsolete or under-utilized facilities
- Policy
  - Changing scheduling policy - different priorities to different customers
  - Changing price policy; influence scheduling and utilization by different customers
- Financial
  - Price policy (as above)
  - Repayment or extension of debt

Figure 30

SIGNAL FLOW BLOCK DIAGRAM

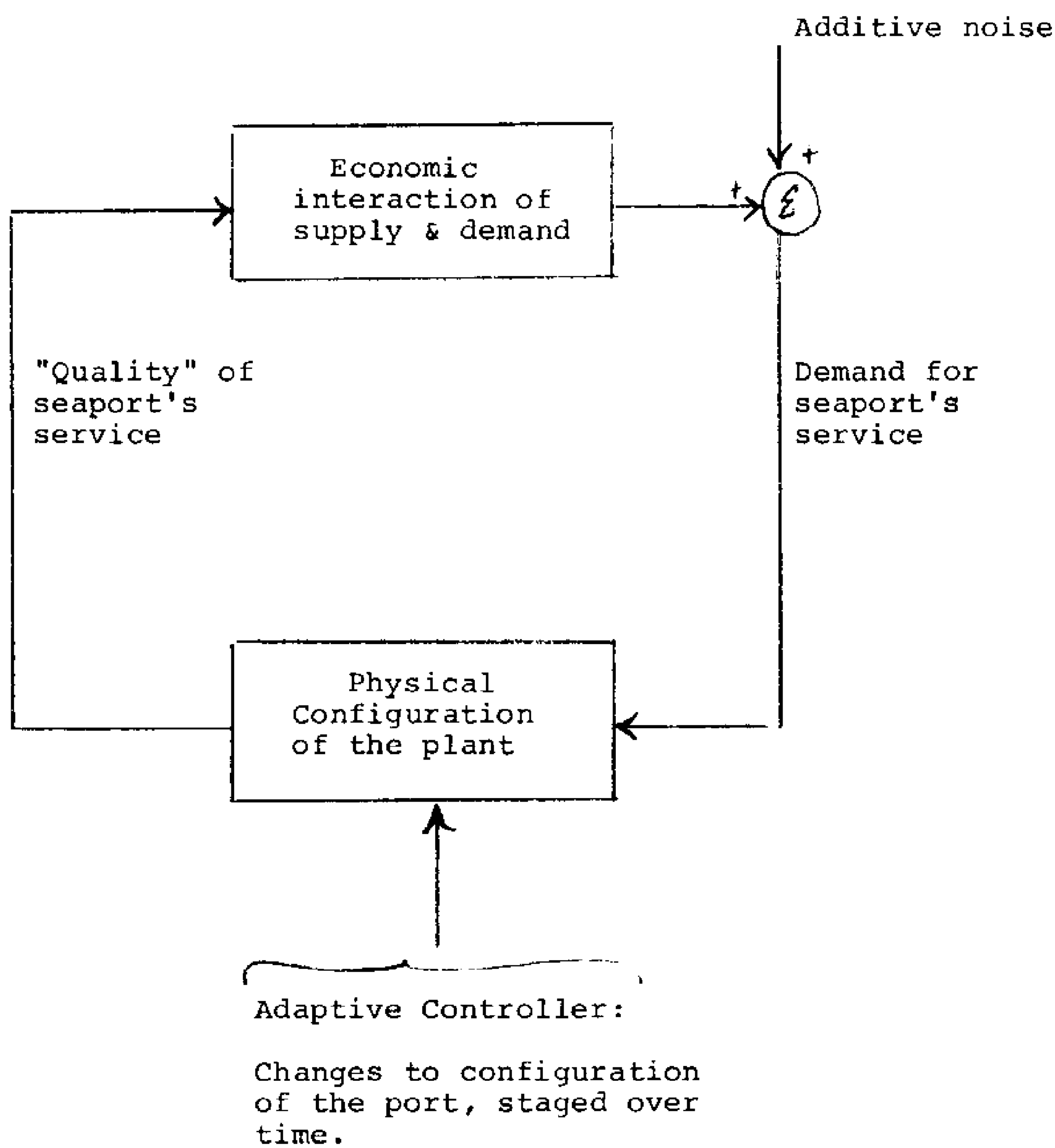


Figure 31

TYPICAL "PERFORMANCE SURFACES"

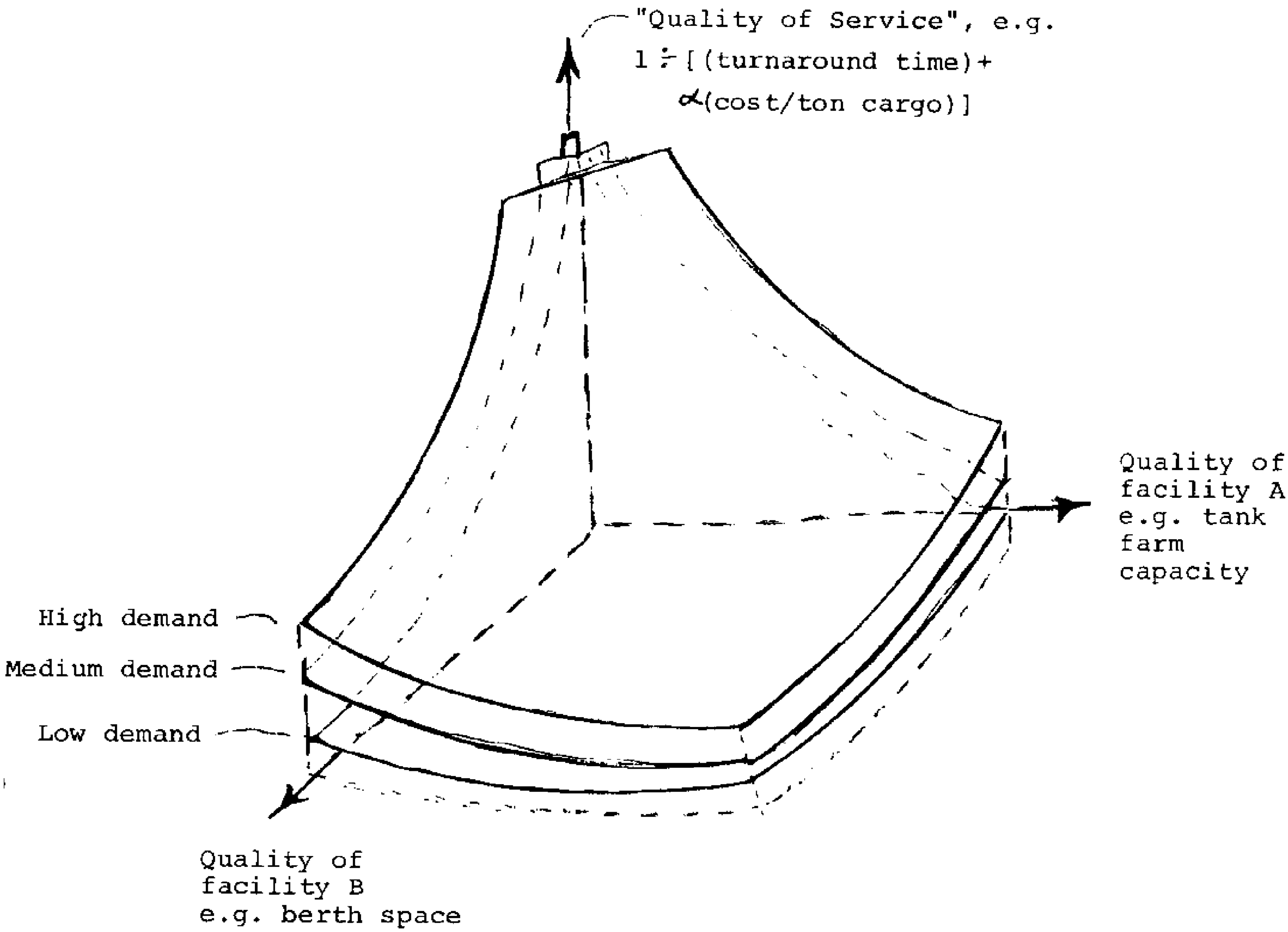
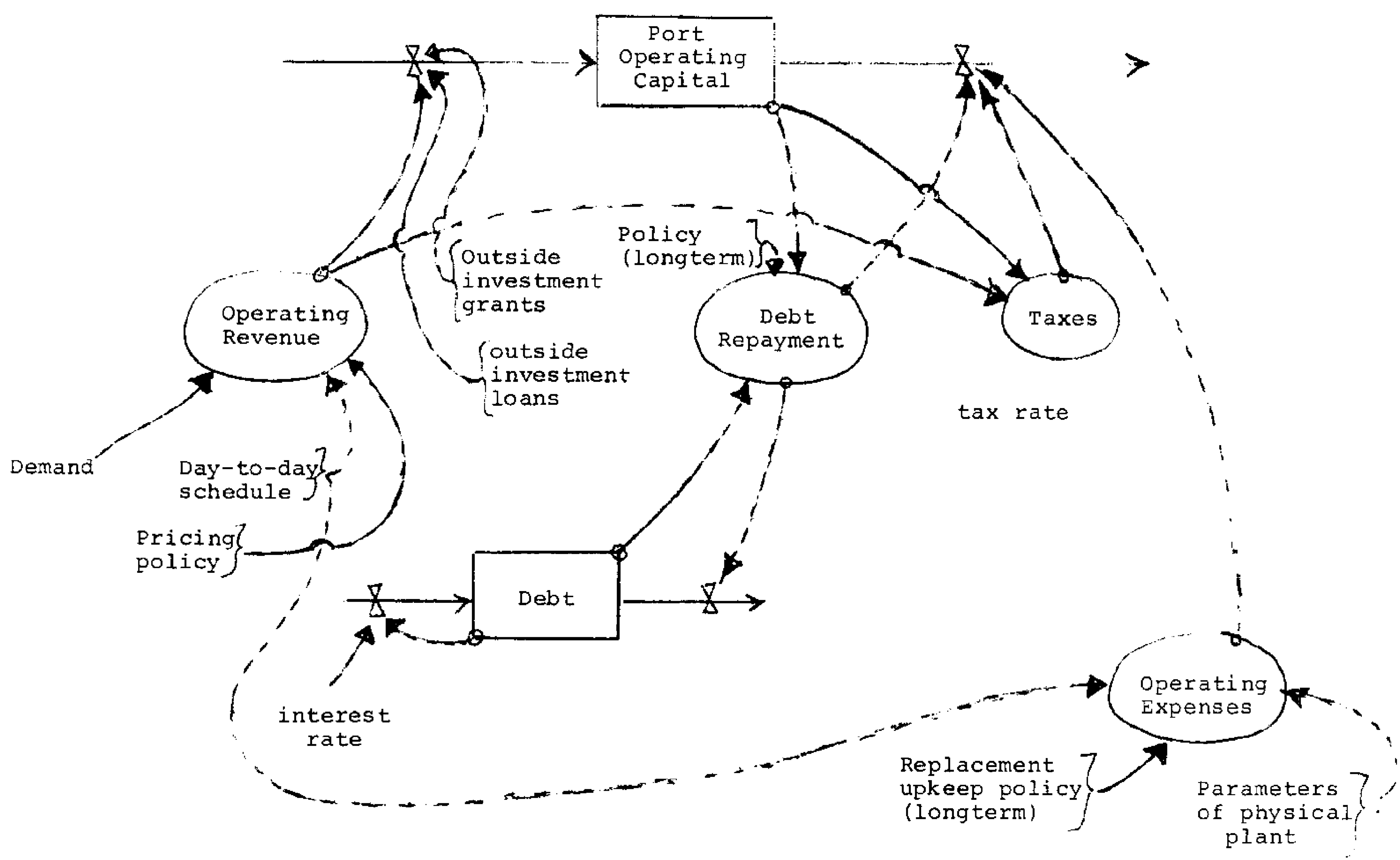


Fig. 32 Port Cash Flows and Financial Sector



Dynamic Programming Formulation of a Simple Oil Port

a. General

As the symmetry argument suggests, the required direction of staging in this sort of problem is not determined by causality. If the system is homogeneous (no external forcing function), as this one is, there is no reason to prefer one direction for time to the other, except numerical stability considerations. Boundary conditions at either (or both) ends of the time interval in question may be incorporated routinely.

If an external input independent of the system and known in advance is present, it is necessary to stage the algorithm towards the specified end condition, starting at the opposite end of the time interval from it. Not to do so produces an optimal policy with an end-point(s) not satisfying the required conditions. If the boundary conditions are split, iterative or policy-space methods must be used. They are not necessary, however, if no exogenous input is present.

The problems originally encountered were not a consequence of the direction of staging, but instead of the fact that the demand state variable was eliminated from the maximization process, and appeared only implicitly in the recursion relation. This is not a correct way to treat a dynamic system; it works only in allocation processes where the plant does not possess "memory."

The simplest brute force approach is the following: For a specified endpoint (zero):

$$f_N\ (\vec{X}) = \underset{\{\vec{U}\}}{\text{Min}} \left\{ C(\vec{X},\vec{U}) + f_{N+1}\ [-\vec{g}\ \ (\vec{X},\vec{U})\ \ \Lambda + \vec{X}] \right\}$$

Where

$f_N(\vec{X})$ = Minimum cumulative cost from state $\vec{X}$ to zero

$C(\vec{X},\vec{U})$ = Cost of using control effort $\vec{U}$ at state $\vec{X}$

$\vec{g}(\vec{X},\vec{U})$ = Plant equations.

For a free endpoint:

$$f_N(\vec{X}) = \underset{\{\vec{U}\}}{\text{Min}} \left\{ C(\vec{X},\vec{U}) + f_{N-1}\,[\vec{g}\,(\vec{X},\vec{U})\ \Delta + \vec{X}] \right\}$$

This means, that for each stage N, we evaluate $f_N(\vec{X})$ for all permissable values of $\vec{X}$; for each such value of $\vec{X}$ we minimize the expression over the set of permissable $\vec{U}$.

$\vec{X}$ is the state vector, and includes, in our case, both demand and capacity. The algorithm described and used creates at each stage N a table for f_N which included only a subset of $\vec{X}$ (capacity), and as a result certain optimal policies were missed.

The most unfortunate consequence of this is the fact that we must generate policy tables at each stage of order n, where n is the dimension of $\vec{X}$. Thus the treatment of problems with $n > 3$ is not practical.

A decrease of dimensionality by 1 is possible via a Lagrange multiplier, but affords no relief for large N:

$$f_N(X_1,X_2,\ldots X_{n-1}) = \underset{\{U\}}{\text{Min}} \left\{ C(\vec{X},\vec{U}) + f_{N-1}[\vec{g}\,(\vec{X},\vec{U})\ \Delta + \vec{X}] + \lambda X_n \right\}$$

Here one of the state variables is left out of the tables f_N and is allowed to run from the specified initial condition as a function of plant dynamics. Different choices of λ will produce different trajectories, so that the true optimum can be found. X must be carried along in the optimal policy tables, however. The Lagrange multiplier is a way of selecting and searching over a subset out of all the time series X (t) which the brute-force alorithm considers. Thus less time and memory is required, by a factor corresponding to the numerical grid size.

There are two drawbacks to this: the algorithm connot now handle split boundary values conveniently, because an initial value of X must be chosen consistent with reality; and the method is not readily extendable to much higher dimension, because to do so requires an M-dimensional search in Lagrange multiplier space, where M is the number of state variables deleted from the policy tables.

This may be practical for small extensions of dimension (four or five additional state variables) but not much more. This is discussed further in a subsequent section.

Two algorithms are derived in detail: a three-dimensional one, and a two-dimensional one. Both are feasible on MULTICS.

The basic assumptions are:

1. The system may be represented by the block diagram of Figure 29

2. The relationship between demand on the seaport and the quality of service it produces is given by the function:

   $G(t,b,d\ (t-\Delta) = q(t)$

   where:

   t = installed tank capacity

   b = installed berth capacity

   τ = time

   $d(\tau)$ = demand

   $q(\tau)$ = quality of service

   Δ = increment in time

3. The effect of quality of service upon future demand is given by the function

   $E\ (q(\tau-\Delta),\ \tau) = d\ (\tau)$

   E is a dynamic system, represented by a time-domain simulation. G is a set of numerical tables, developed from an event simulation of the port facility.

4. $g_n\ (t_n, b_n, d_n)$ = aggregate cost of operating the port facility for a time Δt starting at time $n\Delta t$, where t_n, b_n, d_n are respectively the installed tank capacity, installed berth capacity, and demand, at time $n \cdot \Delta t$.

5. $f\ [t_n - t_{n-1}),\ (b_n - b_{n-1})]$ = installation cost of additional capacity.

6. $h(d\ )$ = weighting function representing the value of maintaining demand d for one time increment.

7. $$C_N = \sum_{K=0}^{N} \left\{ g_K(t_K, b_K, d_K) + f_K\ [(t_K - t_{K-1}),\ (b_K - b_{K-1})] - h(d_K) \right\}$$

C_N = cumulative cost of operating system through stage N.

<u>The Simple 3-d Algorithm:</u> Let

$$C_N = \underset{\begin{Bmatrix} t_i \\ b_i \end{Bmatrix}}{\text{Min}} \left\{ \sum_{i=0}^{N-1} C_i \quad (t_i, b_i, d_i \right\}$$

be the optimal cost associated with a trajectory from stage zero to stage N. ($\tau = 0$ to $\tau = N\Delta\tau$)

But $d_i = E\ [G\ (t_{i-1}, b_{i-1}, d_{i-1})]$

or

$$d_{i-1} = E^{\nabla}\ [G^{\nabla}\ (t_i, b_i, d_i)]$$

Thus we may write the recursion relation

$$C_N\ (t_N, b_N, d_N) = \underset{\begin{Bmatrix} t_{N-1} \\ b_{N-1} \end{Bmatrix}}{\text{Min}} \left[g_{N-1}\ (t_{N-1}, b_{N-1}, d_{N-1}(t_N, b_N, d_N)) \right.$$

$$+ f_{N-1}\ [(t_N - t_{N-1}),\ (b_N - b_{N-1})] - h\ [d_{N-1}(t_N, b_N, d_N)$$

$$\left. + C_{N-1}[t_{N-1}, b_{N-1}\ (t_N, b_N, d_N)] \right] \Bigg\}$$

subject to the constraints on t_{N-1}, b_{N-1} at each stage:

$$t_o \leq t_{N-1} \leq t_N$$

$$b_o \leq b_{N-1} \leq b_N$$

$$d_N - E\ [G(t_{N-1}, b_{N-1}, d_{N-1})] \leq E$$

where G is some small number chosen according to numerical grid size.

A flow chart for this algorithm appears in Figure 29. The flow chart includes compensation for stochastic demand, discussed in the following section. It operates as follows:

1. Construct a table $C_1(t_1,b_1,d_1)$. Given the initial conditions (t_o,b_o,d_o), only particular combinations t_1,b_1,d_1 are feasible; they represent solutions of the plant equation. Determine these by application of the third constraint equation, and enter the corresponding cost in a table $C_1(t_1,b_1,d_1)$. These entries represent the cost of reaching each feasible demand point d_1.

2. Construct a table $C_2(t_2,b_2,d_2)$. Again, only particular combinations (t_2,b_2,d_2) are feasible. Determine these by application of the constraint equation, and enter the corresponding costs in a table.

3. Proceed similarly to construct successive tables C_N. Eventually the situation will arise where two or more states at stage N-1 are capable of producing the same state at stage N (within the numerical approximation of the grid size used). When this occurs, the optimal trajectory (N-1 state) should be determined by a direct search and stored as an entry in the C_N table. Eventually, as the grid "fills up" for large N, the policy tables will contain sufficient information so that the optimal trajectory may be traced back from the final state.

a. Two-dimensional Algorithm, with Lagrange Multiplier.

Let

$$C_N \ (t_N, b_N) = \min_{\substack{\{t_i\} \\ \{b_i\}}} \left[\sum_{i=0}^{N-1} C_i \ (t_i, d_i) - \lambda d_{itt} \right]$$

where d_i, d_{itt} are defined by the plant equations as before.

Then the recursion relation is:

$$C_N \ (t_N, b_N) = \min_{\substack{\{t_{N-1}\} \\ \{b_{N-1}\}}} \Big\{ g_{N-1} \ [t_{N-} \ , b_{N-1}, d_{N-1}(t_N, b_N, d_N (t_{N-1}, b_{N-1}, d_{n-1})]$$

$$+ f_{N-1} \ [\ (t_{N-1} - t_{N-1}), \ (b_N - b_{N-1}) \ ] - h(d_N(t_{N-1}, b_{N-1}, d_{N-1}))$$

$$+ \lambda d_N(t_{N-1}, d_{N-1}, b_{N-1}) + C_{N-1} \ (t_{N-1}, \ b_{N-1}) \Big\}$$

with the same constraints as before.

A flow chart appears in Figure 30. Its operation is similar to the preceding:

1. Given t_o, b_o, d_1 is defined by the plant equations.

Calculate it, and set $C_1 = \lambda d_1$

2. Stage 2: Optimize $C_2 \ (t_2, b_2) = \min_{\substack{\{t_1\} \\ \{b_1\}}} \Big\{ C_1 \ (t_1, b_1)$

$$- \lambda d_2 \ (t_1, b_1) + C_i \Big\}$$

3. Proceed through N stages.

This will define one optimal trajectory (t_i, b_i, d_i) for a given λ, with d_i a dependent variable of t_i, b_i. If λ is small, the trajectory will lead to small d, because {t,b} related costs dominate. If λ is large, the optimum will occur at higher demand:

Thus by trying successive values of λ, we find a family of corresponding trajectories, each of which is the optimum of a specified subset of the set of feasible trajectories. The overall optimum is then the one which leads to the smallest minimum cost, not counting the λ-terms.

b. Generalization to Stochastic Demand

So far we have assumed that the system is deterministic. In this section an extension is proposed which allows for additive noise in the demand signal as shown in Figure 32.

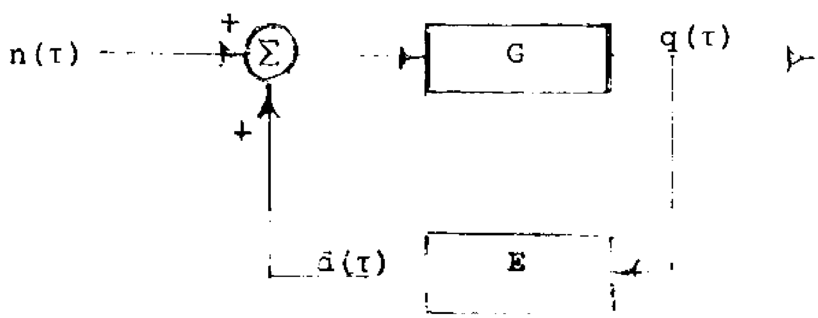


Figure 32

Two methods of dealing with this are discussed: one which is approximate but feasible, and another which views the process as a Markov chain. This is more accurate, but numerically infeasible for a system of larger than second order. The errors resulting from the simpler approximation are discussed below:

Suppose $\Lambda(t)$ is a random variable with mean zero [$E\{N\} = 0$] and a distribution p(n). Then if the seaport transfer function is

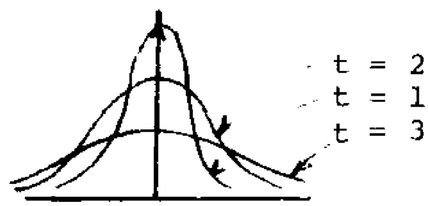
$$G(d+n) = q(d+n)$$

q is also a random variable.

Since in general G is nonlinear, the noise on q is not zero mean; but approximately equal to G[E(d+n)]

The simplest approach is therefore to bias the numerical representation of G(d) by the noise distribution before executing the dynamic programming algorithm. For example, instead of storing G(d) in location d of the numerical performance function, store E[G(d+n)], for an appropriate n. If this is done, the short-term effects of noise are accounted for, and the dp algorithm may be used without change.

However, this neglects an important property of Markov processes: whatever the initial state, the probability distribution of the state tends to "diffuse" over time, as suggested below:



Thus in the distant future, things are far less certain than they are near the present time. So states far ahead in time are less important, and should be discounted somehow in the criteria function. This may be done by introducing an exponential argument of the form:

$$C_N\ (t_N, b_N, d_N) = \underset{\begin{Bmatrix} t_{N-1} \\ b_{N-1} \end{Bmatrix}}{\text{Min}} \Big[e^{-\alpha} C_{N-1}^{(N-1)} (t_{N-1}, b_{N-1}, d_{N-1})$$

$$+ C_{N-1}\ (t_{N-1},\ b_{N-1}, d_{N-1}) \Big]$$

The exponential term reduces the sensitivity of the cost function C_N to later values in time, and sets a practical limit as the maximum value of N required. α should be chosen with regard to the noise variance, so that the time required for $e^{\alpha (N-1)}$ to decay to zero is camparable to the time required for the corresponding Markov chain to decay to a steady state.

The more exact problem is solved elegantly by Howard* and finds an algebraic representation for the steady-state component of the probability transition matrix, and optimizes with respect to it.

However, in the present case his method would require the solution of 10^3 simultaneous equations in 10^3 variables of the recursion, which is clearly impractical. There may be a clever way to get around this (further consideration is suggested) but if so, it is not apparent to the author.

An intermediate approach is to consider the distribution of the criterion function at each stage, instead of simply its expected value.

From a given initial condition, we compute the probability distribution of the succeeding state as a function of the input, and optimize $E[C(\vec{X},\vec{U})]$ instead of $C(E[\vec{X},\vec{U}])$ at each stage.

This means that a numerical representation of the distribution must be included for each entry in the optimal policy table.

After a fairly small number of stages, the process will stabilize, in the sense that the immediate optimal input does not change as further stages are added.

This approach also presents numerical difficulties, because of the size of the policy tables required.

It is found that the expected value approach with discounted future was most effective, although results are slightly suboptimal where the plant is strongly nonlinear or where the variance of the noise is large.

---

*R. Howard, Dynamic Programming and Markov Chains, M.I.T. Press 1963.

Basic Seaport Model Structure

The modeling of the physical makeup and day-to-day operation of a port facility is presented in Figures 33-35. The flow through a port is usually discrete (e.g., ships, containers, tank-cars, palletized loads).

In accommodation of the idea of modeling the entire port operation by "level" and "flow rate", the whole flow from ships entering the approach channel of the port to cargo leaving the backside of the port (and alternatively cargo arriving at backside and ships leaving) can be divided at two points, the loading (off-loading) platform (mooring for lightering and buoy-discharged tankers) and the port end of the inland transportation system. Consequently, there are three principle flow routes which, when jointed together by the appropriate rates and transfer functions, become the flow operations model of the entire port. The three flows are those involving ships, cargo (in the transit sheds and warehouses) and land transports (trains, trucks, pipeline). The division into these particular categories is called for mostly by the fact that such choices minimize the amount of cross-linkage between the flow sectors. We must also note that although these particular flow representations are models of import flow, they are substantially equivalent (with changes and/or additions of arrows) to models of export flow.

The starting point for the flow modeling of ships in the port is the rate of flow of ships into the approach channel. For our purposes this rate is determined by the function generator whose input is vectors describing various parameters of the ships entering the approach. These parameters include ship number, quantity of various cargo types going in, quantity of various cargo going out, ship type, allocation of labor specified by the ship, etc. The number of ships in the approach channel is considered a level and the rate out of the approach channel and into (or through) the anchorage is a function of both the level in the approach and the level of the anchorage.

Flow out of the anchorage may be split three ways: ships go to either break-bulk cargo berths, oil or tankage berths, or container and bulk loading (off-loading) berths. Ships may not come out of the anchorage at all. If forced to spend too much time waiting for a berth or lighter, they may turn around and leave unloaded. There is also cross-flow of ships from one type of berth to another for combination-cargo vessels. This will exist between any of the berths (all combinations are possible) although for clarity only one cross-flow of ships is shown on the diagram. Ship flow out of the berth-utilization levels loaded or unloaded and leave the approach channel level and with it the port itself.

Figure 33
THREE PRINCIPLE FLOW ROUTES

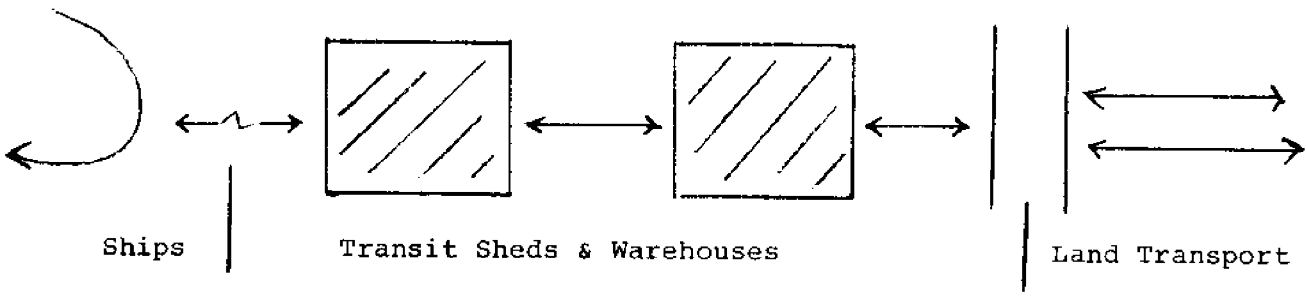
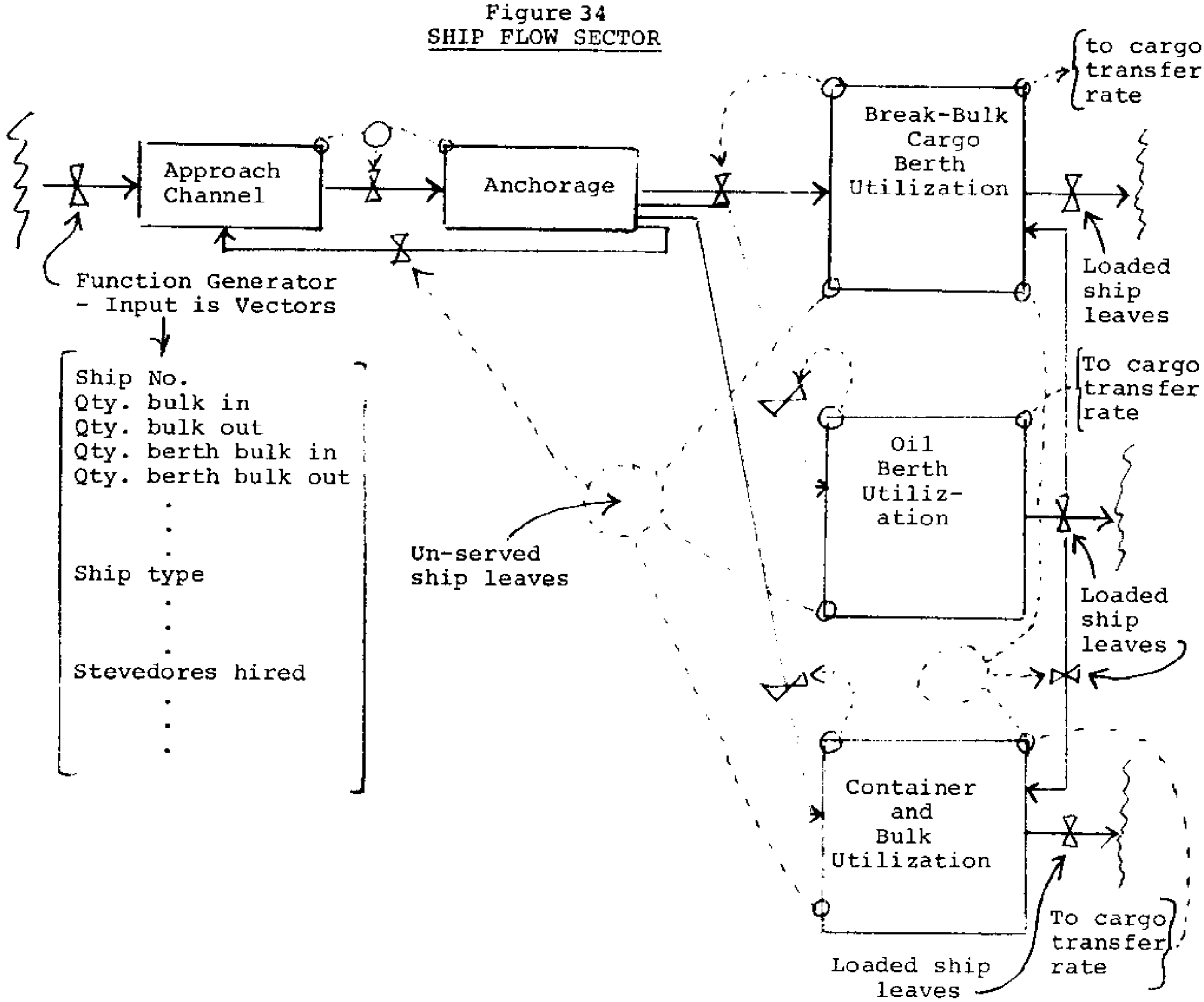


Figure 34
SHIP FLOW SECTOR



Starting with the cargo flow emmenating from the break-bulk cargo berth level of utilization, there is a rate of flow into the transit shed utilization level which is determined by the function describing the ship-to-shed unloading rate. Inputs into this function come from the levels of small cargo berth utilization, equipment (handling facilities) labor allocated to small cargo handling, transit shed utilization and from the warehouse transfer rate.

Flow out of the transit shed can be split three ways. It may go directly to the inland transportation system (rate is exogenous), it may go to a user-owned warehouse on the premises of the port using the intra-port cargo movement facility, or it may go to the port-owned warehouse. The rate of flow from the transit shed to the user-owned warehouse is determined by the same function which determines the ship-to-shed rate of flow except as modified (probably significantly) by an input from the user. The shed-to-port's warehouse rate of cargo flow is a function of the ship-to-shed unloading rate (and of all its inputs) as well as of the levels of equipment and labor allocated to this movement of cargo.

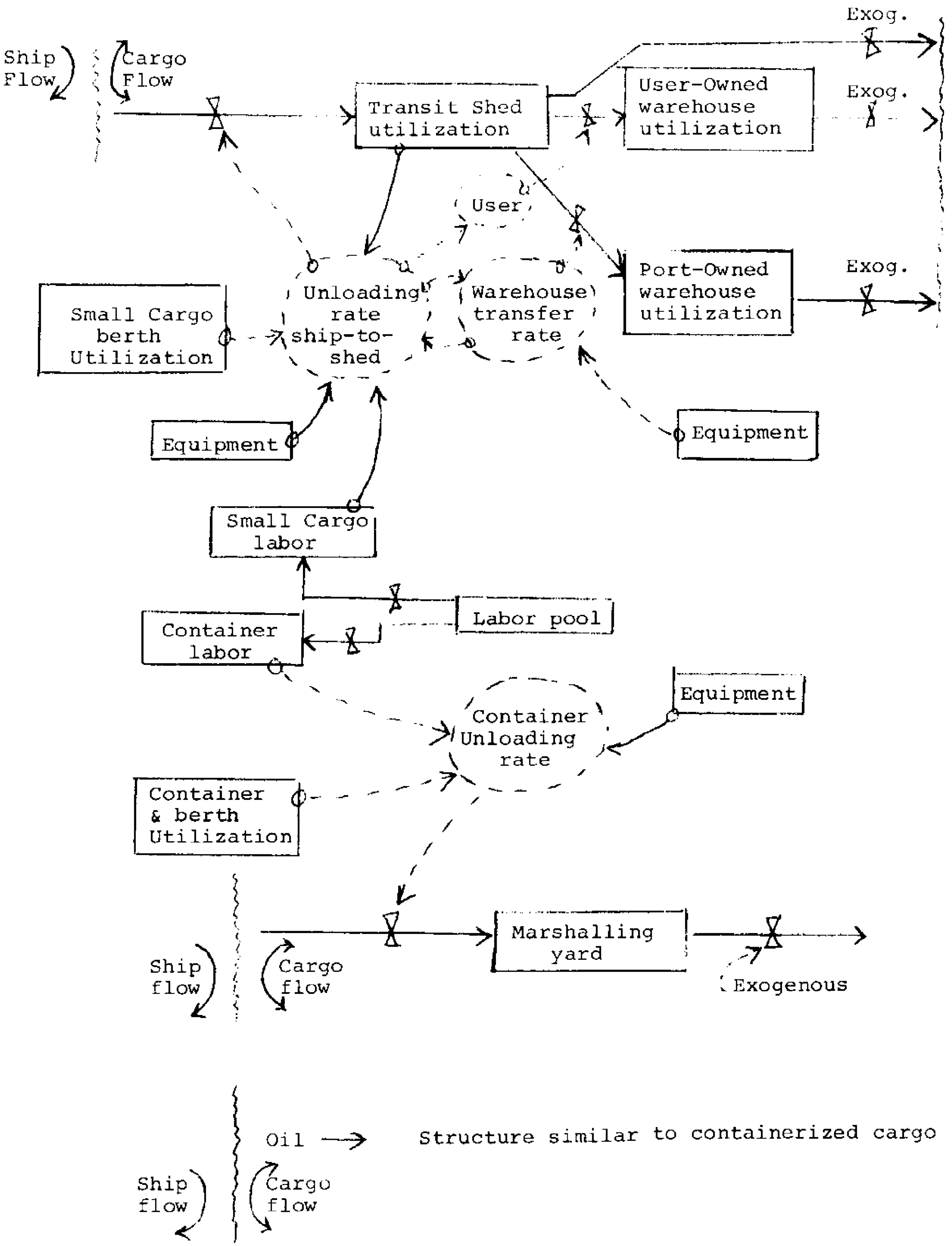
The flow patterns associated with the modeling of the container and bulk handling berth as well as the oil and tankage handling berth are very similar to those described above, although actually much more simplified.

There is interaction across the berth categories in such areas as the labor situation even in the day-to-day operations and in more of the levels in the larger-run outlook.

The overall objectives of this study are to evaluate alternative policy, investment, use and development strategies for U.S. Atlantic Coast ports. Since the total combined capacity of these ports for cargo handling generally is well in excess of demand, some questions of interest are (1) what is an optimum investment in port facilities for the present and future, and (2) what is the optimum allocation of these facilities between the Atlantic Coast ports (e.g. centralized versus decentralized ports, single versus multi-purpose ports). In order to answer these questions our work has broken into two major phases - first the development of analytical tools for modeling the ports and the commodity flow netowrk and second the application of these tools to the Atlantic Coast situation. In this report I will outline the tools that have been developed in the first work phase.

The cost of transporting a volume of goods is considered to be in two parts: (1) a port cost, and (2) an inland transportation cost. The port cost in turn can be divided into: (1) a fixed investment cost of facilities, (2) a variable cost for cargo handling and (3) a congestion cost represented by the time ships spend queuing for port services. The inland transportation costs are freight rates in $/ton for transportation from a port to a hinterland.

Figure 35
CARGO FLOW (TRANSIT SHEDS & WAREHOUSES) SECTOR



The objective function for the system calculates the total cost of cargo flow through the port hinterland network given the port and inland costs as arguments and subject to hinterland demand constraints. The aim of the optimization model is to find the cargo flow pattern that satisfies hinterland demand at the minimum total cost. There are three modeling elements involved in this system: (1) the network flow model that finds the optimum flow pattern given port and inland transportation costs, (2) the port investment cost program that develops economies of scale curves for given port investments and (3) the port simulation model that estimates congestion costs for a given set of port facilities by a computer simulation of port operations.

The major difficulty that has been encountered in representing the port-hinterland distribution arises from the fact that introduction of port congestion costs results in a non-linear objective function. The function is convex, however, and this allows us to use a piecewise linear approximating function.

The port hinterland distribution can then be formulated as a network problem with multiple arcs where the port costs are represented by the source to port arcs, the inland transportation costs by the port to hinterland arcs and the hinterland to sink arcs are used to establish demand constraints. Each port (j) to hinterland (k) arc will have an associated land transportation cost and a zero lower bound constraint. Each of the multiple arcs between the source and a given port will represent one linear segment of the approximated port cost curve. The associated cost will be the slope of that segment (marginal cost) - written C_i for the i^{th} segment. Thus the total cost for a volume V* through a given port where V* falls within the i^{th} line segment will equal

$$C(V^*) = C_1(V_1-V_0) + C_2(V_2-V_1)\ldots C_{i-1}(V_{i-1}-V_{i-2}) + C_i(V^*-V_{i-1})$$

This model will represent port costs correctly only if we can guarantee that marginal cost C_i will be applied only to the i^{th} increment of volume. We can do this by setting the lower bound for the i^{th} arc to zero, the upper bound to (V_i-V_{i-1}) and insisting that the cost function be both convex and have a positive slope for all feasible flow volumes. The convexity and positive slope requirement insures that the cost of arc i (C_i) will be more than the cost of arc j for all j less than i. This in turn guarantees that arc i will not be used until every arc j ($j<1$) has been filled. (Cheapest are filled first) The bounds applied to each arc insure that the i^{th} marginal cost will be applied only to one segment of the cost curve.

Each of the hinterland to sink arcs are used to establish hinterland demand constraints by setting arc lower bounds to the hinterland demand volume. The cost associated with these links is zero.

The network flow model so formulated has been solved by the "out of kilter" algorithm to give port volumes and inland flow patterns for given inland transportation costs and port cost curves. Two problems with this formulation are (1) that it does not distinguish between import and export cargo volume and (2) that it does not directly consider the option of closing a port entirely (eliminating the constant fixed cost). The first problem may be of importance since port congestion costs for a given volume of cargo through port will depend to a great extent on the ratio of import to export flow. A one-way flow will require more ships and will be less efficient in utilization of terminal space than an equal volume of mixed flow. An objective function for a model that distinguishes between imports would be:

$$\text{Cost} = \sum_i f_i \; (X_i, Y_i) + \sum_i \sum_j \; (X_{ij} + Y_{ij})$$

where X_{ij}, Y_{ij} are import flow and export flow respectively between port i and hinterland j

X_i, Y_i are total import and export cargo volume for port i = $\sum_j X_{ij}$, $\sum_j Y_{ij}$

and f_i (X,Y) is the total fixed variable and congestion cost for import volume X and export volume Y in port i - f is non-linear in both X and Y

The constraints to this problem are

$$\sum_i X_{ij} = \text{total imports to hinterland } j$$

$$\sum_i Y_{ij} = \text{total exports from hinterland } j$$

The second difficulty arises from the fact that port fixed costs are carried as constants in the objective function and therefore do not contribute to the solution. In fact, however, in considering the option of closing some ports entirely we wish to allow these fixed costs to become zero when flow-through of the port is zero. In this case the port cost function would be

$$f(X) = \begin{cases} F + V(X) & \text{when } X \neq 0 \\ 0 & \text{when } X = 0 \end{cases}$$

This problem could be formulated as a mixed integer program to consider port closing options.

Port fixed costs and port variable costs include, respectively, the fixed debt obligations for land, buildings, cargo handling equipment in each terminal complex and the labor, fixed maintenance costs incurred directly by cargo handling.

To estimate these costs for container ports we have chosen to idealize a terminal complex as a set of berths, a set of cargo handling units, and a container storage and administration area. The fixed cost associated with berth space and container storage area are estimated from costs of land fill, land improvement and associated buildings. Each cargo handling unit includes the crane and its associated pier equipment - fork lifts, straddle carriers, tractors and chassis. The fixed cost for each piece of equipment is amortized over an appropriate life span to give an annual fixed debt. Operating costs are calculated from the fuel and labor loss for operating each piece of equipment and a fixed overhead for administration, maintenance, etc. The output of this program gives total fixed and variable port cost as a function of cargo throughput.

Diseconomies of scale occur in port costs when the volume of throughput becomes large enough so that congestion and queuing time add expense to the port operations. These diseconomies will be estimated by a computer simulation of port operations. For the purpose of this simulation the port has been idealized as having three potential bottlenecks: (1) due to lack of berths, (2) due to lack of service units (cranes, etc.) within a terminal complex and (3) due to lack of terminal space for storage. The port itself will be a collection of one or more terminal complexes where each terminal complex is a collection of berths all served by a single terminal storage space. Associated with the terminal complex there is also a collection of cargo handling units, each of which can serve any berth.

The port simulation program takes, as input, a description of terminal facilities (number of berths, number of handling units, amount of storage space) for each terminal complex of a single port and a random generation of ship arrivals. Ship characteristics for arriving ships and import and export cargo volume are also assigned by random generation. Thus by specifying mean cargo volumes per ship and mean ship interarrival time, simulations can be carried out for different levels of port throughput. From these inputs port operations are simulated by assigning berths, cranes and storage area to arriving ships, calculating the resulting service times and recording queuing times. The output of the model gives total ship turnaround time (arrival to departure), total ship time at berth (time of assignment to berth until departure time), total unit-hours of service (number of unit serving the ship times number of hours of service) and total volume of throughput. These statistics, summed over all ships in the simulation, give estimates of congestion factors associated with each of the three port bottlenecks. By applying average ship costs per day to the total ship turnaround time and by applying operating costs per hour to the total service unit hours we also get estimates of port cargo handling and congestion costs. These, together with port investment costs, make up the port cost curves that enter the network flow model.

The models outlined above provide the general tools used in the Atlantic Coast port study.

Port Planning Model for the U. S. Atlantic Coast

In evaluating policy alternatives for Atlantic Coast port development, we have assumed the following to be our objectives:

1) To derive a measure of port capacity and, using this measure, to determine the level of efficiency at which these ports are presently operating.
2) To estimate the most efficient distribution of cargoes between ports that will satisfy given import and export constraints.
3) To estimate the most efficient future investment and operating policies for each port given import and export constraints.

The cargo distribution model includes nine Atlantic Coast ports and at least twice that number of inland origin/destination areas (hinterlands). Nine of these hinterlands represent the immediate vicinities of the nine ports. To complete the picture we should also include the overseas origins and destinations; however, due to the complexity involved with adding a foreign port into our model and due to the total lack of information concerning foreign inland origins and destinations, we assume that the total cost of foreign inland transportation and sea transportation for a given cargo is the same regardless of which of the nine ports it is delivered through.

An additional dimension to this picture is the classification of cargoes by cargo type. A classification of cargoes into container, break-bulk, liquid bulk and dry bulk systems is used and we consider the transportation and handling systems for each of these cargo types to be independent. That is to say, for example, the level of congestion within the container cargo system has no influence on the efficiency of any other cargo system. While this is not entirely true since all cargo systems do use some port facilities in common (e.g. pilots, tugs, labor force, port access roads), it should not cause significant errors in our results. Assuming independence then allows us to consider and optimize each cargo system and cargo flow independently among ports.

The discussion following will consider one cargo system although the result will be a formulation that can be applied independently to each system.

Port Strategy Model

Elements of the model

The cost of transporting a volume of goods is considered to be in two parts: (1) a port cost and (2) an inland transportation cost. Sea transportation and foreign inland transportation costs are excluded from consideration since they are assumed to be equivalent for all U.S. ports.

The inland transportation costs are assumed to be related to the distance over a shortest possible route from the port to the hinterland. Thus, for each port/hinterland combination, there exists a freight rate in dollars per ton of cargo. The matrix D_{ij} will contain the distances between port j and hinterland i. (In general the subscript j will refer to ports and i to hinterlands.) If R is a function relating distance to transportation cost then $I_{ij} = R(D_{ij})$ is the cost in \$/ton of transportation over distance D_{ij}.

The port cost for cargo handling can be considered in three parts: (1) fixed costs (reflecting primarily capital investment) of port equipment and facilities, (2) direct costs of cargo handling (e.g. labor cost) and (3) ship delay costs.

An amortized capital cost for the facilities in port j is included in the fixed costs represented by F_j in dollars per year. The cargo handling costs are represented by H_j in dollars per ton of cargo. This cost may include, for example, a labor cost in dollars per hour per gang divided by a cargo loading rate in tons per hour per gang to give a handling cost in dollars per ton. The ship cost represents the total cost of the time spent by ships in port for the purpose of loading/unloading (handling) their cargo. This time is expressed as N_j ship-hours per year and is the summation of hours spent in port j by all ships handling cargo in port j within a year. The total cost of this time is PN_j where P is the vessel cost for each hour spent in port.

The total ships' time in port (N_j) is derived from two components: ship-hours of idle time (Q_j) and ship hours of cargo handling time (L_j). Idle time (Q_j) can be the result of waiting for a berth and/or the delay due to attempting to run a terminal complex at higher than its design capacity. When there is no congestion in port the idle time (Q_j) will be zero since ships need not wait for berths or equipment. When congestion occurs, however, Q_j will be some increasing function of the volume of cargo flowing through the port since congestion will be related to cargo volume.

Cargo handling time, however, can be assumed to be linear with the volume of cargo flowing through the port by assuming some constant cargo loading/unloading rate (B_j) for the port. In this case ship-hours are:

$$N_j(V_j) = V_j/B_j + Q_j(V_j)$$

where V_j is the cargo volume passing through port j (tons per year) and B_j is the cargo handling rate (tons per hour) so that N_j is in units of ship-hours in port per year.

The function Q_j is not straightforward, however. It is derived through a simulation of port operations for a given frequency distribution of ship arrivals. The simulation generates ship arrivals randomly from this frequency distribution, assigns ships to berths, assigns unloading and storage space to handle each ship's cargo, and in the process calculates the total idle time (Q_j) for these ships to handle a given cargo flow through the harbor (V_j).

The port's cost effectiveness curve

The total port cost in dollars per ton of cargo (T_j) can now be expressed as a function of cargo volume V_j. It is:

$$T_j(V_j) = F_j/V_j + H_j + N_j(V_j)P/V_j$$

where F_j/V_j is the annual fixed cost ($/yr) distributed over the cargo volume using these facilities (in tons/yr), H_j is actual cargo handling cost ($/ton) and $PN_j(V_j)/V_j$ is the cost of ship time in port distributed over the cargo volume handled in that time.

Substituting for $N_j(V_j)$:

$$T_j(V_j) = F_j/V_j + H_j + P/B_j + Q_j(V_j)P/V_j$$

This function, representing port costs in dollars per ton as a function of cargo volume, is a convex function (it is U shaped). This is apparent since the first term F_j/V_j is decreasing with V_j and approaches zero while the last term is an increasing function of V_j (after some value of V_j ship queuing time increases as cargo volume increases). The middle two terms are constant.

Thus it is clear that $T_j(V_j)$ has a minimum point (point at which economies of increased scale balance costs of increased congestion) and that point (V_j*) is the most efficient operating point for port j.

The curve $T_j(V_j)$ will be called the port's cost effectiveness curve, and the value V_j* will be called the port's design capacity.

The first objective of this work is to determine these port cost effectiveness curves and capacity values in order to determine the efficiency levels at which the port presently operates.

It is expected that the ports under consideration will be found to be operating well below their design capacities, so that an analysis of these curves will give some real estimates of the cost of present port inefficiencies.

Port optimization

Given the present cost effectiveness curves for each port under consideration it will now be of interest to determine the distributions of cargo flows from hinterlands through ports that minimizes the overall cost of cargo handling. For this problem we will let V_{ij} represent the total cargo flow (tons/yr) between hinterland i and port j. Then:

$$V_j = \sum_i V_{ij}$$

The problem now is to find the V_{ij}'s for all i and j that minimize total cost K:

$$K = \sum_j T_j(V_j)V_j + \sum_i \sum_j I_{ij}V_{ij}$$

subject to

$$\sum_j V_{ij} = A_i$$

and

$$V_{ij} \geq 0$$

where I_{ij} is the inland transportation cost and A_i is the total volume of cargo flow to and from hinterland i.

Now substituting for total port cost $(T_j(V_j)V_j)$ the objective function becomes:

$$K = \sum_j F_j + H_jV_j + P(V_j/B_j + Q_j(V_j)) + \sum_i \sum_j I_{ij}V_{ij}$$

with

$$V_j = \sum_i V_{ij}$$

and ST

$$\sum_i V_{ij} = A_i \qquad V_{ij} \geq 0 \text{ for all } i,j$$

The solution to this problem is not simple since the function $Q(V_j)$ (ship idle time) introduces a non-linearity that cannot even be analytically defined. Steepest ascent techniques are not immediately feasible because of the prohibitive computational cost of handling about 200 variables (such as 19 hinterlands x 9 ports). There is one promising approach, however. If we can limit our search variables to the 9 V_j's (port volume) instead of the almost 200 V_{ij}'s, steepest ascent searches may be feasible - provided that the function has only a single peak. This can be done by fixing port costs by setting values to the V_j's and solving the resulting simple transportation problem. For fixed values of V_j the problem of minimizing:

$$K = \sum_j F_j + H_j V_j + P(V_j/B_j + Q_i(V_j)) + \sum_i \sum_j I_{ij} V_{ij}$$

reduces to the simple problem of minimizing:

$$\sum_i \sum_j I_{ij} V_{ij}$$

subject to

$$\sum_i V_{ij} = V_j$$

$$\sum_j V_{ij} = A_i$$

$$V_{ij} \geq 0 \text{ for all } i,j$$

Of course V_j's must be such that

$$\sum_j V_j = \sum_i A_i$$

This is a readily solvable transportation problem. Adding port costs for the given set of V_j's now gives us a value of K for any set of port volumes (V_j's). If we can guarantee (and we think we can) that K has a single peak, optimization may be approached by a steepest ascent search over the nine variables V_j.

Optimizing future port development policies

So far we have considered the problem of determining port capacity and optimizing cargo flows for a single, given mix of cargo facilities at each port. The problem of determining optimal future port investment in equipment and facilities, or optimal port operating policies, introduces several new variables. The number of berths, the number of cranes, the number of storage units (transit sheds, oil tanks, etc.) as well as the policies for assigning ships to port facilities all become optimization variables.

If we let M_j be one element in the matrix of port facility alternatives at port j (for example think of M_j as a vector in which the elements are: number of berths, number of cranes, number of storage units, etc.), then the port parameters F_j,

H_j, B_j and Q_j (a function) are all functions of M_j. The terminal cost $T_j(V)$ now is:

$$T_j(V) = \frac{F_j(M_j)}{V} + H_j(M_j) + \frac{PN_j(M_j,V)}{V}$$

so that a different cost curve (T(V)) is associated with each port investment alternative. Each of these cost curves will have an optimal value T* at V* such that T* = T(V*). The pair (T*,V*) thus represents the optimal port cost ($/ton) and the design capacity for a given port investment alternative (M_j). The problem now is to determine from among the set of feasible investment alternatives those that can achieve a given design capacity (V*) for a minimum port cost(T*). As an example consider a simple case where number of berths and number of cranes are the only port variables. Assume that each berth costs $2 million and each crane costs $1 million. Also assume that ships generally occupy one berth and usually (but not always) can be serviced by at most three cranes simultaneously. Then, clearly, for an investment of $10 million the alternatives of providing one berth with eight cranes or four berths with two cranes are impractical while, on the other hand, the alternatives of providing either two berths served by five cranes or three berths served by four cranes appear practical. (The more efficient of the latter two alternatives can be determined only by simulation.) Thus, out of a large number of feasible investment alternatives a relatively small number of practical alternatives can be identified on the basis of the relationships between the cargo handling components. The identification of these practical alternatives can be done by a study of shoreside cargo handling procedures for each cargo type.

Associated with this set of practical alternatives will be a set of values (T^*,V^*) representing the port's design capacity and port cost at design capacity. Port simulation--to develop the port cost effectiveness curve $(T(V))$--is the tool to map investment alternatives to the set of points (T^*,V^*). A lower bound to the set of (T^*,V^*) points represents the curve of "efficient" investments for a given port. Each point on this curve represents the most efficient (lowest) port cost for a given design capacity. This function (call it $T^* = g(V^*)$) can be defined as infinite when $V^* = 0$. The point $T^* = \infty$, $V^* = 0$ then represents the alternative of closing a port and thus shutting off all cargo flow through it.

The final problem now is to establish efficient investment curves for each of the nine ports. We are then in a position to determine the efficiency of current port investments and to recognize an optimal future investment policy for each port. The problem calls for us to find the values of V_{ij} that minimize:

$$\sum_j V_j^* g(V_j^*) + \sum_i \sum_j V_{ij} I_{ij}$$

where $g(V_j^*)$ is the efficient investment function for port j and

$$V_j^* = \sum_i V_{ij}$$

and subject to

$$\sum_j V_{ij} = A_i \qquad V_{ij} \quad 0 \text{ for all } i \text{ and } j$$

The optimal values of V_j^* then define points on the $g(v^*)$ curve that represent specific investment policies. These investment policies are estimates of the optimal investment alternatives.

Simulation of Port Operations

A basic simulation model for multi-berth ports was developed to study the effect of port characteristics, layout, and capacity on physical operations and resulting facility utilization. The model is an expanded version of the UNCTAD* model built in 1969 and permits random ship arrival and various berth assignment policies. In our model port facilities were carried through the land exit side, and include major berth equipment, storage areas and the port-land interface.

The various models described briefly here and in more detail in the companion volume "Port Design and Analysis Methodology", were used to evaluate the capability and sufficiency of Atlantic ports by running the models for individual ports, sets of regional ports or the total set of the nine major Atlantic ports. The latter exercise was undertaken for major bulk and unitized commodity flows to investigate the effect and tradeoff of alternate port use on investment requirements and total transportation costs.

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*UNCTAD "Port Development" 1969.

6.0 Future of Atlantic Ports

The U.S. Atlantic ports which were considered among the world's most modern and effective a decade ago are rapidly becoming obsolete. The only exceptions to this statement are probably the new container terminals, some dry bulk berths, and certain specialized cargo berths such as LNG and chemical terminals. Most of the improvements in port facilities are made on a parochial basis which result in vast imbalances in over and under capacity. The rapid changes in ocean transportation technology, coupled with physical form changes in many important commodities and modifications in trade patterns, force a re-evaluation of port investment and operating policy. This is particularly pertinent now, when the U.S. becomes increasingly dependent on bulk commodity imports and exports. The competitiveness in these trades is greatly dependent on the cost of ocean transportation which is a function of the size of vessel used. The U.S. is among a rapidly diminishing number of major trading nations without the capability of handling large bulk carriers, which emphasize the economy of size. The populous and resource poor Atlantic states are particularly dependent on low cost bulk imports, the flow of which can only be assured through an effective Atlantic port industry.

6.1 Present and Future Needs

One of the major problems in the use and planning of Atlantic ports is the serious imbalance in commodity flows of all types. This fact is becoming more pronounced as commodities are increasingly carried by specialized ships and handled by specialized facilities. It applies equally to general cargo, containerized or unitized cargo, liquid bulk cargo and dry bulk cargo. In general cargo including containerized or unitized cargo imports exceed exports by a factor of two to one, while most liquid or dry bulk cargo flow in either export or import. Considering containerizable cargo for example Figure 29 we find that total imports are expected to continue to exceed total exports by a factor of two at least until 1980. It is also found that this trend is universal on all trade routes with the exception of trade with the Caribbean where exports exceed imports by a factor of 3. (Tables 59 and 60). Far East (Japan) imports for example exceed exports through Atlantic ports by a growing factor which was 6.4 in 1968 and may reach nearly 8 in 1980. Although recent currency realignments may affect this trend, it is not obvious that the effect will be pronounced or permanent.

Considering major dry bulk cargoes moving through Atlantic Ports such as grain, iron ore, bauxite, coal and phosphate rock we find that these commodities accounted for over 65 million tons of exports and 25.1 million tons of imports during 1970. These commodities represent over 85% of dry

Figure 36

Containerizable Trade Through U. S.
Atlantic Ports (in 20 ft. Equivalents x 10^{-3})

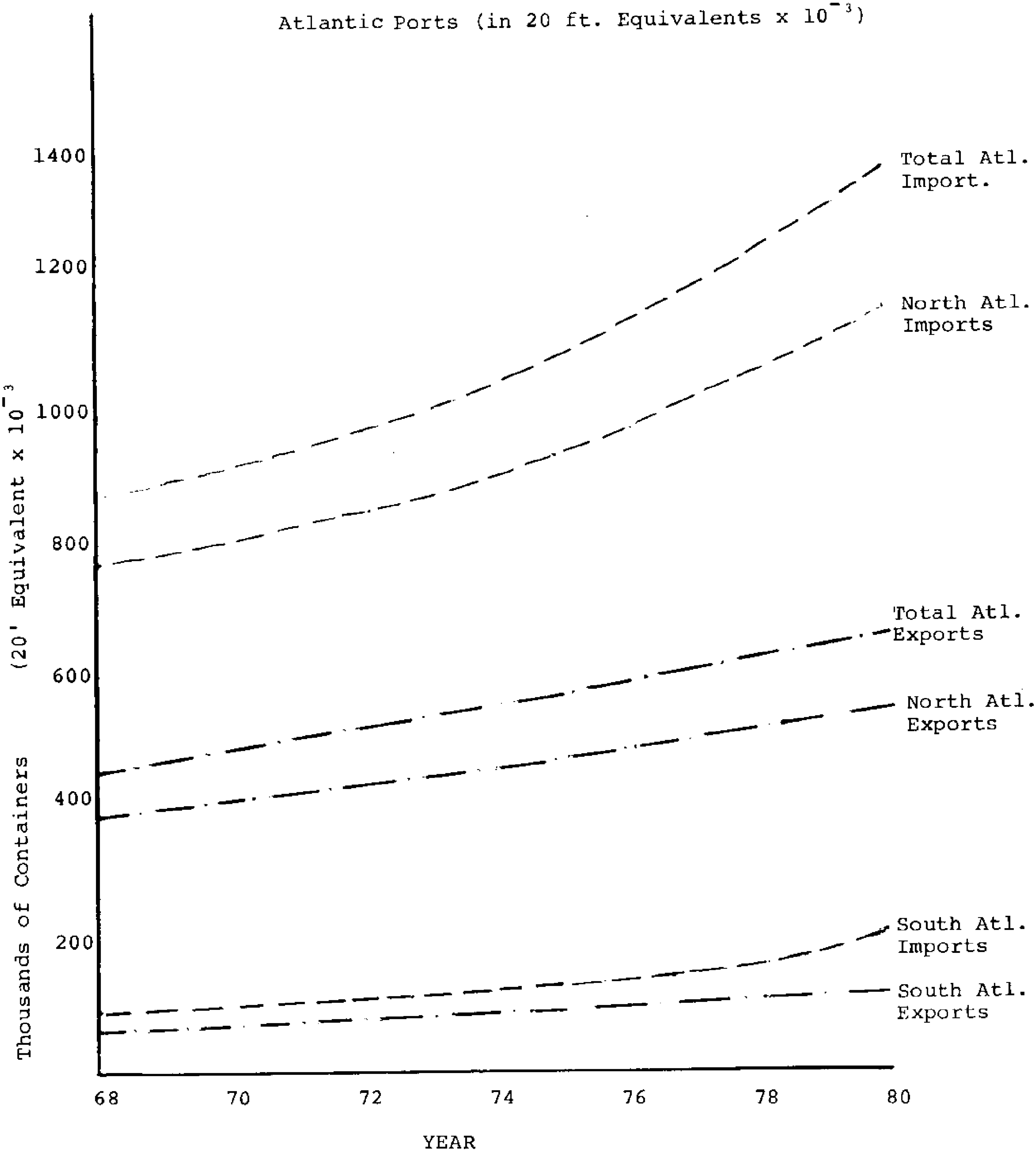

Table 59

U. S. WATERBORNE IMPORTS, CONTAINERIZABLE COMMODITY FLOWS, 1968-1980
(Thousands of 20-Foot Container Equivalents)

FOREIGN TRADE AREA	U. S. SEABOARDS					
	North Atlantic			South Atlantic		
	Actual 1968	Estimated 1975	1980	Actual 1968	Estimated 1975	1980
Caribbean	15	19	23	3	4	7
East Coast, South America	45	54	67	2	3	4
West Coast, South America	50	60	74	2	2	3
West Coast Central America, Mexico	3	3	4	*	*	*
Gulf Coast Mexico	8	10	12	*	*	*
United Kingdom/Erie	63	76	94	4	5	8
Baltic, Scandinavia	48	58	71	2	3	4
Bayonne-Hamburg Range	141	171	211	18	26	40
Portugal/Spain	17	21	26	1	1	1
Azores/Mediterranean	78	94	115	8	11	17
West Coast of Africa	27	33	40	*	*	*
South and East Africa	21	25	31	1	1	2
Australia	25	30	38	7	10	15
India/Persia	30	37	45	24	34	54
Malaysia	20	24	30	1	2	3
Far East-South	56	67	83	9	14	21
Far East-North Area	123	149	184	14	21	32
Canada	3	4	NE	-	-	NE
TOTAL FOREIGN TRADE AREAS	772	935	1,149	95	137	214

*Less than 500 containers per year

Note: Colums may not add because of rounding.

Table 60

U. S. WATERBORNE EXPORTS, CONTAINERIZABLE COMMODITY FLOWS, 1968-1980

(Thousands of 20-Foot Container Equivalents)

	U. S. SEABOARDS					
	North Atlantic			South Atlantic		
	Actual	Estimated		Actual	Estimated	
FOREIGN TRADE AREA	1968	1975	1980	1968	1975	1980
Caribbean	46	52	64	11	16	19
East Coast, South America	21	23	29	1	2	2
West Coast, South America	17	19	24	1	1	2
West Coast Central America, Mexico	3	4	5	*	*	*
Gulf Coast Mexico	3	3		*	*	*
United Kingdom/Erie	31	34	43	3	5	6
Baltic, Scandinavia	19	21	26	*	*	*
Bayonne-Hamburg Range	89	100	124	17	24	29
Portugal/Spain	5	6	7	*	*	*
Azores/ Mediterranean	42	47	59	8	12	14
West Coast of Africa	9	10	13	1	2	3
South and East Africa	14	15	19	2	3	2
Australia	18	20	25	2	3	4
India/Persia	25	28	35	2	3	3
Malaysia	5	5	7	1	1	1
Far East-South Area	24	27	33	6	9	11
Far East-North Area	19	21	26	7	10	12
Canada	--	1	NE	--	--	NE
TOTAL FOREIGN TRADE AREAS	390	436	541	63	91	110

*Less than 500 containers per year

Note: Colums may not add because of rounding.

bulk commodities in the foreign trade moving through Atlantic ports and over 60% of all dry bulk commodities moving through these ports. The major dry bulk cargoes in the domestic trade appear to be gypsum, cement and coal. Grain exports (Table 61) through Atlantic ports are insignificant as a percentage of U.S. grain exports; on the other hand over 5.4% of U.S. iron ore imports are usually handled through these ports (Tables 62 and 63). Alumina and Bauxite Imports (Table 64) are relatively unimportant. Coal exports are nearly exclusively handled through Atlantic ports (Table 65) and accounted for over 50 million tons in 1971. Florida ports handle practically all U.S. phosphate rock exports (Table 66) which amounted to over 10 million tons annually in recent times. This trade is expected to increase rapidly and reach 18 million tons in 1980 and 27 million tons by the turn of the century.

Considering liquid bulk we find that crude petroleum and petroleum products constitutes over 98% of all liquid bulk commodities handled through these ports, and amounted to over 289.6 million short tons per year in 1969 (Tables 67 and 68). Out of this nearly 120 million s.t. were foreign imports, while nearly 100 million s.t. were petroleum products shipped or received in coastwise trade. About 82 million tons of crude petroleum and products were handled in internal or local trade. Projections of demand for petroleum handling in Atlantic ports is difficult because it is effected by many complex decisions, such as:

1) The development of deep draft offshore terminals on the Atlantic seaboard.
2) The construction of the Trans-Alaskan pipeline.
3) The development and use of offshore deep draft terminals in the Bahamas, Newfoundland, Nova Scotia and New Brunswick.
4) The development of deep draft terminal on the U.S. Gulf coast.
5) Changes in Oil Import Policy.
6) National Energy Policy
7) Others.

For the purposes of this study it was assumed that landed crude costs would continue to escalate at about 5% per year in 1972 dollars, that a gulf deep draft terminal will be established by 1978, while the Atlantic seaboard will have its first operating deep draft terminal in 1981. The Alaskan pipeline is assumed to be completed and operating by 1977. Imports through the Atlantic ports are expected to about double from 1969 to 1980 and then level off at 240 million s.t. Coastwise shipment on the other hand will only increase by about 70% as an increasing percentage of imports consists of petroleum products. By 1985 petroleum flow is expected to level off as the results of the various policy factors come into play.

General cargo movement consisted of 29.7 million tons in 1969 of which 10.3 million tons were exports, 7.3 million tons imports, 4.0 million tons were handled in coastwise trade and

6.1 million tons in internal and local trade. The volume of general cargo handled through Atlantic ports has leveled off for a number of years. Increases in dry non-bulk commodity movements appear to effect only containerized cargo. As a result the demand for transfer of general cargo is not expected to increase. Special cargoes amounted to 6.8 million tons in 1969 of which over 4.5 million tons were export cargoes. These movements are fairly irratic and projections of future demands are difficult to make.

A summary of cargo flow (1969) is given in Table 69 which indicates the overriding importance of bulk commodity handling.

Table 61 Grain Exports via U.S. Atlantic Ports

(Millions of short tons)

	1970	1980	2000
North Atlantic	4.0	4.4	4.9
South Atlantic	0.3	0.4	0.6
Total	4.3	4.8	5.5
% of National Total	5.2	5.1	4.6

Table 62 Imports of Iron Ore by Port (1969)

Port	Percentage of Total National	Tons in Thousands
Philadelphia	28.9	12,295
Baltimore	24.8	10,541
Camden	.4	186
Total	54.1	23,022

Table 64 Imports of Bauxite and Alumina
(1969)

Port		
Baltimore	0.6 (Alumina)	101 (Bauxite)
Other Atlantic Ports	0.6 (Alumina)	99 (Bauxite)
Total	1.2	200

Source: U.S. Waterborne Imports, Bureau of Census, Report SA-305

Table 63 Iron Ore Imports through Atlantic Ports*
(Million of long tons actual ore)

Origin	1970	1980	1990	2000
Canada	4.4	4.8	4.8	5.4
Venezuela	9.6	10.3	11.9	14.6
Brazil	1.1	1.5	2.0	2.6
Peru-Chile	1.2	1.6	2.0	2.4
West Africa	2.0	2.5	3.3	4.0
Other	0.2	0.3	0.5	0.7
Total	18.5	21.0	24.5	29.7

*Source: U.S. Deep water Port Study--Commodity Studies and Projections, Institute for Water Resources, Department of Army, IWR Report 1972-8.

Table 65 U.S. Exports of Bituminous Coal by Port, 1968, 1969, and January to June 1971

(Thousands of short tons)

<table>
<tr><th>Port</th><th>1968</th><th>1969</th><th>1970</th><th>Jan.-June 1971</th></tr>
<tr><td>Philadelphia</td><td>295.4</td><td>377.5</td><td>297.4</td><td>65.7</td></tr>
<tr><td>Baltimore</td><td>2,441.6</td><td>2,658.7</td><td>4,722.9</td><td>2,020.6</td></tr>
<tr><td>Norfolk</td><td>24,409.8</td><td>27,669.3</td><td rowspan="2">46,221.7</td><td rowspan="2">20,115.1</td></tr>
<tr><td>Newport News</td><td>7,522.9</td><td>9.374.7</td></tr>
<tr><td>Total</td><td>34,669.7</td><td>40,080.2</td><td>51,242.0</td><td>22,201.4</td></tr>
</table>

Source: 1968 and 1969 -- special tabulation by RRNA of data in U.S. Department of Commerce, Bureau of the Census, Foreign Trade Division, Extracts from SA705 U.S. Exports; 1970 and 1971 -- U.S. Department of the Interior, Bureau of Mines, U.S. bituminous coal exports by Customs District, International Coal Trade, February and August 1971.

Table 66 Waterborne U.S. Exports of Phosphate Rock by Port of Shipment

Port	1968		1969	
	Short tons	Percent	Short tons	Percent
	(1,000)		(1,000)	
Tampa	8,804	83.0	8,198	82.1
Jacksonville	907	8.5	811	8.1
Boca Grande	712	6.7	712	7.1
Beaufort-Morehead	69	.7	258	2.6
Norfolk	68	.6	--	--
Baltimore	19	.2	--	--
Other	21	.2	14	.1
Total	10,600		9,993	

Source: RRNA tabulation from data in U.S. Bureau of the Census, U.S. Waterborne Merchandise Exports, SA-705, Annual.

Table 67 Waterborne Movements of Crude and Petroleum Products through Atlantic Ports

(millions of short tons)

		1969	1975	1980	1985
Foreign	Import	119.2	170.0	224.0	240.0
	Export	0.6	-	-	-
Coastwise	Receipt	71.1	109.0	126.0	135.0
	Shipment	26.5	35.0	46.0	50.0
Internal or Local	-	81.7	100.0	120.0	125.0
	Total	289.6	414.0	516.0	550.0

Table 68 Summary of Foreign Trade and Intercoastal Movements of Crude Petroleum and Products by North Atlantic Ports and Port Areas, 1968

(In millions of net tons)

Port or port area	Crude			Residual fuel oil			Other products a/		
	Imports	Coastal rects.	Total	Imports	Coastal rects.	Total	Imports	Coastal rects.	Total
Portland, Maine.	21.5 b/	--	21.5	1.1	0.4	1.5	a/	3.2	3.2
Other Maine and New Hampshire..	--	--	--	1.6	a/	1.6	0.1	1.8	1.9
Boston, Mass....	0.1	a/	0.1	6.6	0.2	6.8	0.2	9.6	9.8
Other Mass......	--	--	--	1.2	0.2	1.4	0.1	2.1	2.2
New Haven, Conn.	--	--	--	2.2	0.5	2.7	0.1	5.1	5.2
Other Conn. and Rhode Island...	--	0.3	0.3	2.9	2.6	5.5	a/	9.1	9.1
New York, N.Y...	10.5	8.1	18.6	25.6	1.5	27.1	4.2	7.8	12.0
Other New York..	--	--	--	1.2	0.4	1.6	--	4.5	4.5
Delaware River, Trenton, N.J. to the sea (inc. the Schuylkill River).........	26.6	21.8	48.4	6.7	1.1	7.8	0.2	3.9	4.1
Baltimore, Md...	0.5	0.1	0.6	2.8	0.2	3.0	0.2	2.1	2.3
Hampton Roads and York River, Va.............	2.2	0.2	2.4	2.2	0.1	2.3	0.1	1.2	1.3
North Carolina..	0.1	--	0.1	0.5	a/	0.5	a/	1.6	1.6
South Carolina..	--	--	--	1.3	a/	1.3	a/	1.6	1.6
Georgia.........	a/	0.2	0.2	0.6	0.1	0.7	a/	0.7	0.7
Florida.........	a/	--	--	5.1	0.7	5.8	0.3	6.7	7.0
Total.........	61.5	30.7	92.2	61.6	8.0	69.6	5.5	61.0	66.5

a/ Gasoline, kerosine, and distillate fuel oil.
b/ Transit traffic to Canadian refineries.
Source: U.S. Department of the Army, Corps of Engineers, Waterborne Commerce of the U.S., Part 1, Waterways and Harbors: Atlantic Coast, 1968.

Table 69 Summary of Cargo Flow (Millions of Tons)
(1969)

		Foreign		Coastwise	
	Total*	Import	Export	Receipt	Shipment
Dry Bulk	122.8	30.4	47.4	5.1	4.8
Liquid Bulk	289.6	119.2	0.6	71.1	26.5
Container Cargo	11.3	6.9	2.1	0.9	1.4
General Cargo	29.7	10.3	7.3	2.2	1.8
Special Cargo	6.8	4.5	0.5	1.1	-
Total	453.6	170.3	57.3	80.4	34.5

*Totals include Internal and Local Cargo Flow

6.2 Developments to Meet Projected Demand

There are many ways to translate current and projected cargo transfer demand into facility requirements as discussed in Section 4.0. Capacity measures though, depend on many non-physical factors. As a result only general comments on the sufficiency of existent and contemplated port facilities can be made here.

Some of the basic performance measures for terminal productivity are reviewed in section 4.3 and relevant data is presented in Table 5.1.

General Cargo - Many piers and other facilities were built or modernized since World War II. In fact available general cargo berth length in Atlantic port was increased nearly 50% since that time. Improved handling rates resulting from better equipment and higher labor productivity, better berth utilization resulting from increased ship sizes, and the leveling-off of general cargo movements have resulted in appreciable over capacity of port facilities. Total projected general cargo movements are 32.0 million tons in 1975 rising to 33.9 million tons by 1980. Using the general measure of capacity (150 - 180,000 s.t./year) we find, that we will continue to have a capacity of well over double of the most optimistic forecasts.

Container Cargo - Container cargo movements, which reached nearly 1.4 million (20' equivalents) or 11.3 million short tons in 1969. These are expected to grow to 2.04 million or 16.8 million tons by 1980. This growth although significant is far less than the phenomenal increase in container movements from 1960 to 1970 when movements practically doubled every 2-3 years. Conservative estimates of container terminal capacity available in 1975 is 3.2 million containers/year. This mark is not expected to be reached before 1988. It therefore appears that ample container terminal capacity exists although the distribution of available terminals results in large imbalance in the percentage utilization of capacity.

Dry Bulk Cargo - Much of the dry bulk movements are handled over proprietary terminals and facilities. The total capacity of the available terminals would be ample to meet present and near term future need if such movements were continued on small to medium size dry bulk carriers. Bulk carrier technology has changed radically in recent years. Larger unit ship sizes and increased transfer rates are in common use now. There is also a distinct trend towards more effective use of physical form in which various dry bulk commodities are handled.

Slurry movement of dry bulk commodities is increasingly attractive and has been used successfully in moving coal, ore and other commodities. Similarly other form changes are feasible and attractive. They will be increasingly used. As a result of the above consideration it must be conceded that although Atlantic ports offer sufficient dry bulk transfer capacity, the economy of use of existing facilities is by and large not attractive for the medium or long term future. Deeper draft terminals with more effective integration to large capacity feeder transfer systems are required, which take full advantage of the optimum physical form of particular dry bulk facilities. It appears that at a minimum we require two new large deep draft (55'-70') dry bulk facilities (serving Hampton Roads and Delaware - New York).

Liquid Bulk Cargo - Liquid bulk consist primarily of crude petroleum products and chemicals, most of which are handled over proprietary facilities. In fact less than 1% of these cargoes are handled over publicly owned and operated terminals. Petroleum movements are expected to increase from 289 million s.t. in 1969 to 516 million s.t. in 1980. Imports account for 35-40% of this volume. The 144 existing tanker berths in Atlantic ports have the capacity for handling over 400 million s.t./gear based on achievable utilization. On the other hand their draft is severely limited as pointed out in Section 4.3. The economy of size in long distance petroleum transport has made the small and medium size tanker obsolete. The maximum size tanker that can be accommodated in one of these points has a deadweight capacity of about 80,000 DWT. The transport costs of the average ton of imported crude (using average hauling distance) using such tankers is more than double that incurred if a VLCC or Mammoth tanker (200-280,000 DWT or 350,000 DWT plus) is used. At current worldscale rates this implies a cost differential of over $300 million in 1969 and over $500 million in 1975. It is obvious that the magnitude of these potential savings imposes the requirement for serious consideration of deep draft tanker terminals. Various such proposals have been received and a number of preliminary design developed. (Delaware Bay Transportation Company, Machiasport, Massport, Maritime Administration, etc.) While the majority of these proposals are for artificial island type terminals, floating stable platform, single or multipoint mooring and submerged terminals may prove equally attractive, less expensive and more flexible. A decision on offshore deep draft terminals on the Atlantic seaboard is required, to assure effective flow of crude to the energy starved eastern part of this country. It can be readily shown that the potential environmental risks in constructing and operating such a terminal are no more significant than continued and increased use of the multitude of obsolete tanker terminals located largely in congested waters of inner harbors and other densely used waterways. A discussion of environmental impacts though is beyond the scope of this report.

6.3 Competitive Aspects and Capacity Voids

After the big surge in port construction in the 1950s which resulted in U.S. facilities which bec me the envy of the rest of the world, port development slowed down appreciably. Our Atlantic ports were among the few capable of accommodating the "supertankers" of the 1950s then, but have since been overtaken by practically every major world port. The only exception to the above comment is the development of specialized container terminals,where the U.S. Atlantic ports led the rest of the country and the world.

Under present and near term future conditions the Atlantic ports suffer a competitive disadvantage in general cargo, dry bulk, and liquid bulk transfer. Not only are the existing facilities largely antiquated and their depth (draft) severely limited, but many also suffer from lack of modern transfer equipment, inadequate access, inefficient feeder connections and restrictive work rules. Most of the capacity voids are technological as has been pointed out. In many cases incremental improvement and maintenance costs are not justified economically when compared with the potentials of new facilities which provide a step improvement in ship size and cargo transfer rates that can be handled. Such new facilities also offer technological opportunities which cannot be achieved by improvement of existing facilities.

"Studies on the Future of Atlantic Ports"

7.0 Conclusions and Recommendations

The imbalance in port capacity by geographical distribution and facility types has reached enormous proportions. It appears, that we have a vast oversupply of general cargo facilities and more then sufficient container terminals, though the latter are distributed over a number of ports, some of which are not expected to participate in intense deep ocean container movements. In fact the developing pattern and operating needs of capital intensive containerized transportation favours a very limited number of major container ports. Remaining container ports will in all probability be delegated to secondary coastal and short distance container transport or container load distribution/consolidation functions.

A major gap exists in the availability of efficient, deep draft, and large capacity dry and liquid bulk cargo terminals. Not only does this lack introduce major cost penalities resulting from use of inefficient ocean transport and port facilities, but it may also constrain our future ability to handle the increasing quantities of such commodities required to sustain the U.S. economy, because of the lack of sufficient shipping capacity of the size our ports can accommodate and the basic throughput capacity of existing terminals.

The major problem in U.S. Atlantic ports appears to be the total lack of coordination of port development. Not only are ports planned, developed, and operated on a unilateral basis

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and without consideration of national requirements, but also federal responsibility and regulation of port development and operation is maintained by 23 separate federal agencies, whose jurisdiction or decision domain is often ill defined and lacks distinct interpretation.

While the independence and competitive operation of our port authorities is to be encouraged, some form of regional or national port planning appears essential, as requirements and needs for port developments outpace the abilities of individual ports. Modern port technology favours large single or limited purpose facilities with throughputs or capacities which greatly surpass that of a conventional port. As a result future ports will meet regional requirements which in turn demands a regional planning approach to assure unbiased and effective decision making.

Formal methods for regional port planning, as well as port analysis and design are available now. Port development will greatly benefit by the use of such methods.

APPENDIX A

MULTIPLE SEAPORT TRANSPORTATION NETWORK WITH QUADRATIC COSTS

by

Ron Parsons

Table of Contents

MULTIPLE SEAPORT TRANSPORTATION NETWORK WITH QUADRATIC COSTS

INTRODUCTION

The intent of this work is to provide techniques for the study of the interactions between cargo-handling seaports serving a common region. In particular, an attempt is made to detail the relationships governing the relative volumes of the cargo flows through the seaports. The set of seaports is visualized as being imbedded in the transportation network responsible for the movement of various types of cargo from a set of inland sources, such as the industrial areas of a country, to a set of overseas destinations (Figure 1). The total system is composed of:

Sources:	inland origins of cargo
Land transportation:	rail, highway, and water links between sources and ports
Ports:	cargo-handling seaports
Sea lanes:	sea transportation links between ports and overseas destinations
Destinations:	overseas ports

Each source generates steady streams of various types of cargo, fixed percentages of which are to be transported to each of the destinations. Clearly, there are several routes by which a unit of cargo could travel from a source to a destination.

The cost for shipment along any of these routes is the sum of three charges:

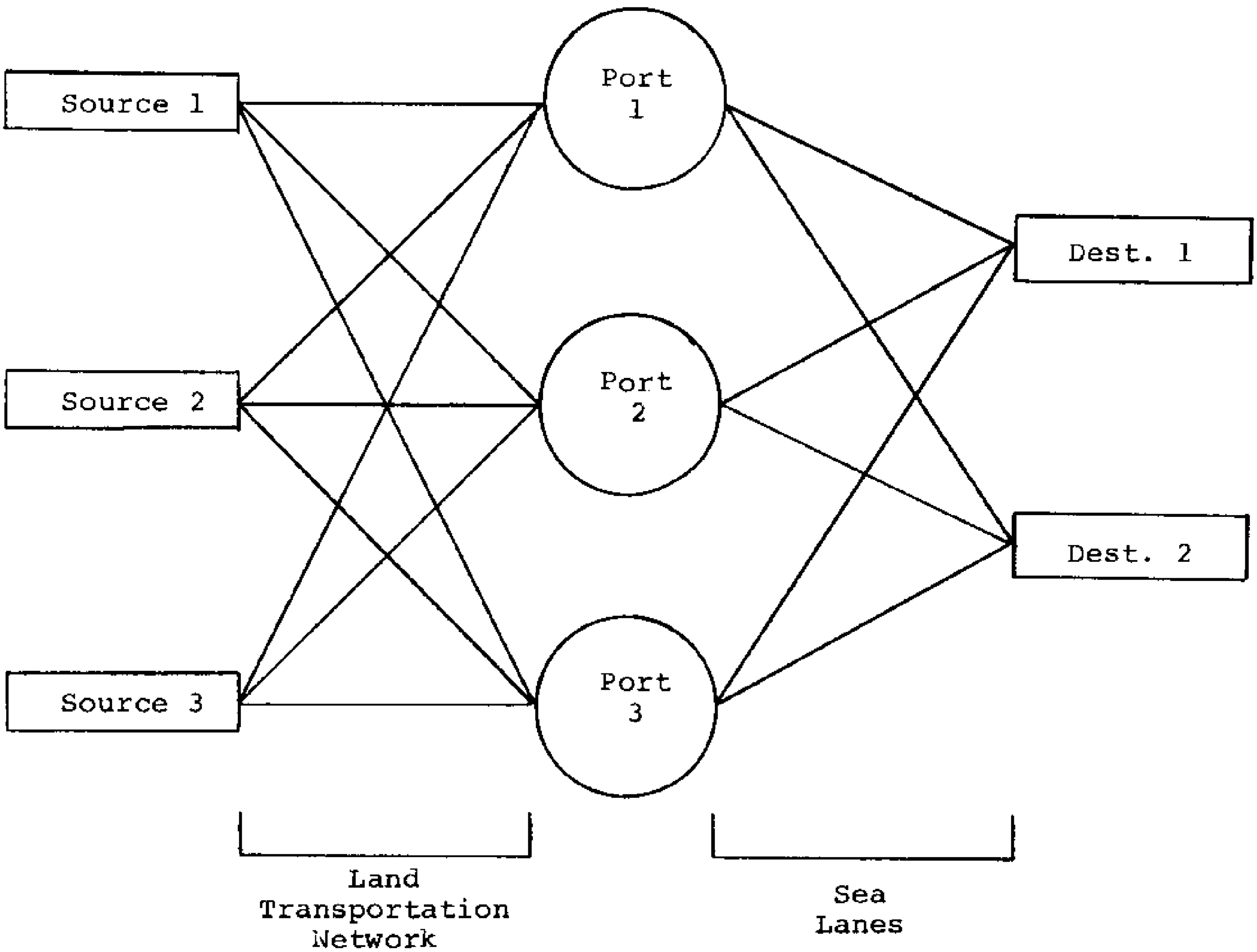

Source 1
Source 2
Source 3
Port 1
Port 2
Port 3
Dest. 1
Dest. 2
Land Transportation Network
Sea Lanes

Figure 1

1) Land transportation charge
2) Sea transportation charge
3) Port charge

The first two of these are flat cost/unit rates, with the charges being dependent upon the cargo type and the route taken. Both the land and sea transportation links are assumed to have infinite capacities and no constraints on allowable cargo mixes. The port charge is composed of two parts: a flat cost/unit charge similar to that for the land and sea links, and a variable charge representing the costs of port congestion. This second charge includes all extra costs of shipment delays, such as increased warehouse occupancy, spoilage, customer annoyance, etc.

This charge is a function of the level of congestion of the port which, in turn, is a function of the total demands made on the port's services. Thus, the port charge is a function of the port's cargo throughput. Also, various constraints are imposed on the allowable cargo mixes and total throughput of each cargo type.

All the above charges are levied against the sources. It is assumed that each source has a management system which determines the routing of that source's cargo through the transportation network. Now, given all the above, the core of the problem is to determine how the sources should route their cargo so as to minimize the costs incurred.

In this paper, this seaport transportation network model is rewritten as a quadratic programming problem. The problem is shown to be amenable to solution by the Dantzig Simplex algorithm for quadratic programming.

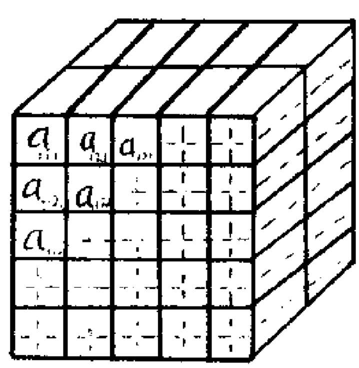
MODEL COMPONENTS

The following sections outline the structures of each component of the system described above. The equations given, although simple, require the use of many subscripts. The following table of subscripts may clarify the meaning of the various terms:

- i refers to a cargo type (container, break-bulk, bulk, etc.
- j refers to a destination or overseas port
- m refers to a port
- n refers to an inland cargo source

Source

Each source continually generates each type of cargo at a steady rate (tons/day, containers/day, etc.). Fixed percentages of each type of cargo produced at each source must be shipped to each destination. Thus, if there are i types of cargo, j destinations, and n inland sources, the sources can be characterized by a three-dimensional array of numbers:



a_{ijn} = quantity/time of cargo i that must be shipped from source n to destination j

The table entries could be time-varying functions to represent, for instance, general economic trends in the region. This would require repetition of the solution algorithm for each significant change in the values of these functions. For the present, these functions will be considered as constants.

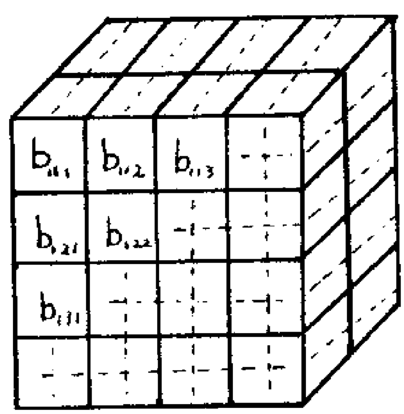
Land Transportation Network

The links connecting the sources and ports represent rail and highway freight transfer routes. In this work, they are assumed to be of infinite capacity, with fixed charging rates. The assumption of infinite capacity is justified by the easy availability of trucks and the tremendous capacity of highway networks. It is assumed that the railroad network can modify its freight schedules in order to supply any demand for freight transfer.

It should be noted that the main limiting factors for rail and road freight capacity are usually imposed by the transshipment points. That is, the freight handling capacity of these modes of transportation is set by the rate at which the vehicles can be loaded and unloaded at the link terminals. One can assume that these limits first appear at the port terminal. This being the case, such limits can be effectively modeled as being imposed by the ports themselves. One should therefore view the land transportation network as being confined to the loading terminals at the sources and the highway and rail links to the ports. The marshalling yards and unloading areas at the ports are considered as parts of the port model.

In the present formulation, only one link connects each source to each port. This link represents the lowest-cost transportation link available. That is, assume a particular source was connected to a particular port by three transportation modes: rail, truck, and waterway. Assuming that the source wishes to minimize its costs, it would route cargo only on that mode that had the lowest cost/unit charge. The other two modes can be ignored.

The land transportation charging policy is rather straightforward and constant in time. The charges levied against the sources are linear with respect to the amount of cargo shipped. If there are n sources, i cargo types, and m ports, the charging policy can be expressed as a three-dimensional array of constant coefficients:



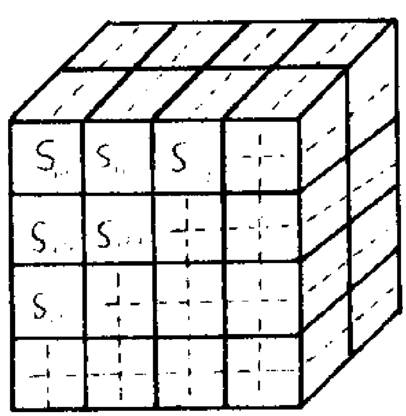
b_{imn} = cost/unit of shipping cargo i from source n to port m

One can easily raise objections to this outlook, on the basis that other factors than straight costs should be considered. Such factors as shipment delays and average percentage of cargo lost or destroyed are ignored in this formulation although they may be of prime importance in real cargo scheduling. In a future model formulation such matters will be included, explicitly. However, to do so here would complicate the model considerably. Since this is an initial attack on the problem, it was felt best to leave the matter in the simplest possible form.

Such factors can, however, be implicitly modeled by assigning them fixed costs/unit and adding this to the land transportation charge. If these factors are such as to preclude shipment over a particular route, the land transportation charge should be set at a very large value.

<u>Sea Lanes</u>

The waterborne transportation system is similar to its land-based analogue. By proper rerouting of ships, any particular port-destination link can achieve near-infinite capacity. Also, the limitations on discharge and loading rates are considered to be functions of the port activities alone. The charging policy is again straightforward, time-invariant, and linear. As such, it can be represented by a 3-dimensional array of constant coefficients:



S_{imj} = cost/unit for shipping cargo i from port m to destination j

Port Model

In this study, a seaport is considered as being contained within a control boundary that serves both land and sea transportation links. Thus, the model for a port must encompass all aspects of cargo handling from one mode of transportation to another. This is not to imply that the model must detail all cargo handling operations, but rather that it be of such a form that the effects of modification of any section of the operation can be implicitly modeled.

As this study is primarily concerned with relative magnitudes of cargo flow rates along the links of the entire transportation system, the port model need only generate those values that affect cargo routing. For simplicity, it is assumed that the only factor involved in cargo routing is the cost/unit levied against the sources for cargo handling. This charge is composed of two factors: a minimum shipping charge and an indirect charge. The former is a flat rate representing a lower bound on cargo handling costs. It is the minimum cost for moving cargo from rail or highway transportation links to a ship's hold under optimal conditions (marshalling yards operating smoothly, immediate transfer to transit shed possible, low transit shed occupancy time, rapid loading onto ship possible, etc.).

The latter charge represents all increases in expenses due to a state of congestion at the port. 'Port congestion', in this case, is a rather loosely defined term. In general, it indicates the degree to which rapid cargo flow is impeded as increasing demands are made on port facilities. In a situation of great port congestion, for instance, it is assumed that ships are forced to wait in anchorage due to a lack of empty berths, cargo movement in transit sheds is hampered by piling of cargo, railroad and truck marshalling yards are characterized by unloading delays due to crowding, bureaucratic delays become excessive, etc. Such delays tend to increase throughput time, leading to increased costs in the forms of cargo spoilage, costs of increased warehouse occupancy times, costs of transit shed use, customer annoyance, etc.

In this model, it is assumed that port congestion can be represented by a linear function of cargo flow through a port:

$$Y_{im} = \sum_n \sum_j X_{ijmn}$$

X_{ijmn} = rate of flow of cargo type i from source n through port m to destination j

Y_{im} = rate of flow of cargo type i through port m

$$W_m = \sum_i w_{im} Y_{im}$$

W_m = congestion of port m

ww_{im} = congestion coefficient for cargo type i for port m

It is also assumed that increases in the total cargo-handling costs are proportional to the degree of port congestion:

$$c_{im} = e_{im} + h_{im} W_m$$

c_{im} = total cost/unit for shipping cargo type i through port m

e_{im} = minimum shipping charge/unit for cargo type i in port m

h_{im} = port congestion cost/unit coefficient for cargo type i in port m

It is further assumed that there exist a variety of limitations on possible cargo mixes and rates of cargo flow. Such limitations are modeled by simple linear constraints:

$$\sum_i \sum_j \sum_n F_{hijmn} X_{ijmn} \leq D_{hm} \qquad h = 1, 2, \ldots, H$$

F_{hijm} = constraint coefficient for port m, cargo type i, destination j, source n, constraint equation h

D_{hm} = constraint for port m, constraint equation h

Scheduling

The routing of cargo through the transportation network is assumed to be controlled by management systems associated with the sources. These systems independently attempt to route their source's cargo in such a way that all of it is delivered to the proper destinations and the total cost incurred by the source is minimized. There are two sources of interaction between these routing systems: the port constraints and the port cost structure.

The constraint interaction arises because the port constraints are functions of the total cargo flow through a port, irrespective of the cargo's origin. Several sources may have to compete for the privilege of shipping cargo through a low-cost but heavily constrained port. It is not clear which source should be allowed to use the port's limited capacity.

The cost structure interaction is due to the fact that the cost/unit for shipping a particular cargo type through a particular port is dependent upon the total quantity of goods passing through the port:

$$C_{im} = e_{im} + h_{im} W_m$$

$$W_m = \sum_i w_{im} Y_{im}$$

$$Y_{im} = \sum_n \sum_j X_{ijmn}$$

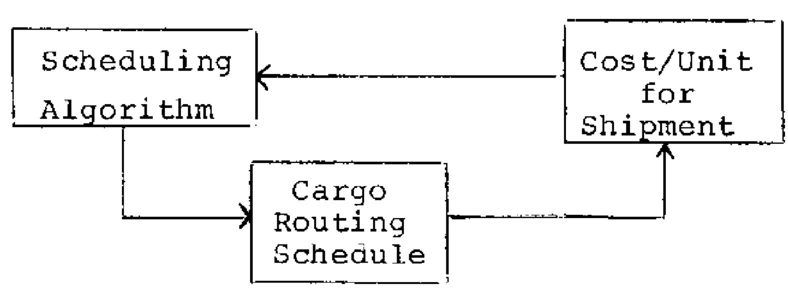
C_{im} = cost/unit

e_{im}, h_{im}, w_{im} = constant coefficients

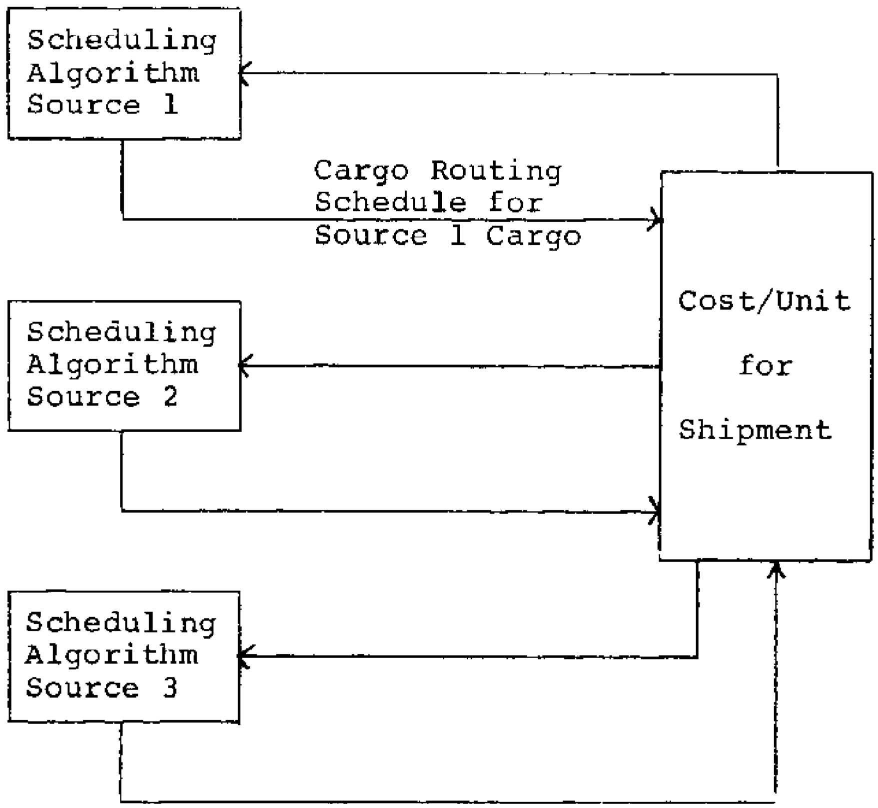
X_{ijmn} = rate of flow of cargo type i from source n through port m to destination j

Thus: $$C_{im} = e_{im} + h_{im} \sum_i w_{im} \sum_n \sum_j X_{ijmn}$$

The set of X_{ijmn} is set by the sources' scheduling algorithms, which accept as input the charging rates, C_{im}. Thus, the charging rates are functions of the cargo routing schedule, which is a function of the charging rates:



However, each source has its own scheduling algorithm:



These interactions between the scheduling algorithms render nearly impossible a straightforward solution to the problem of determining the optimal cargo routing schedules. The fact that each source is attempting to minimize its own shipment costs implies that there are several objective functions in the problem. Simultaneous minimization of interacting objective functions is difficult, to say the least. There are, however, two means by which one can circumvent these difficulties.

The first is to combine the separate objective functions. This implies that scheduling will be done by some agency superior to the sources' management systems. This agency attempts to route all cargo in the system so as to minimize either total shipment costs or, perhaps, to minimize some weighted sum of the shipment costs charged to each port. This same criterion is applied to determine which source should use a heavily constrained port.

The second technique is to use straightforward simulation of the evolutionary development of the schedules. The first step would be to use the above technique to get a 'good' cargo routing schedule. The scheduling algorithm for one source would then be allowed to modify the cargo routing schedule for the cargo originating at source one so as to minimize its costs. At the conclusion of this process, a Monte Carlo method would select another source, and this source's algorithm would be allowed to modify its cargo routing. This process would be repeated until the overall routing schedule either converged to a stable solution or settled into oscillation.

The second technique is probably the better. This implies the need for two objective function formulations: one to generate the total costs incurred by all sources (a value to be minimized by the superior agency) and one to give the costs incurred by a single source. One might immediately say that the first formulation is merely the sum of the second formulation for each source, but this is not directly true. In the first objective function, all the X_{ijmn}'s are variables, while in the second only those X_{ijmn} such that n refers to the source in question are variables. That is, if one is minimizing the costs incurred by source N, all X_{ijmN} are variables while all X_{ijmn} with $n \neq N$ are constants. Source N has no control over the cargo flows originating at any other source. The importance of this distinction is apparent in the matrix formulation of the objective functions.

The first and second formulations of the objective functions are:

$$t = \sum_i \sum_j \sum_m \sum_n (b_{imn} + s_{ijm} + C_{im}) X_{ijmn}$$

$$t_n = \sum_i \sum_j \sum_m (b_{imn} + s_{ijm} + C_{im}) X_{ijmn}$$

t = total cost incurred by 'superior agency'

t_n = cost incurred by source n

Subject to:

$$a_{ijn} = \sum_m X_{ijmn} \qquad \text{for all } n, i, j$$

and:

$$\sum_i \sum_j \sum_n F_{hijmn} X_{ijmn} < D_{hm} \qquad h = 1, 2, 3, \ldots, H$$

with:

$$C_{im} = e_{im} + h_{im} W_m$$

$$W_m = \sum_i w_{im} Y_{im}$$

$$Y_{im} = \sum_j \sum_n X_{ijmn}$$

We can use the last three equations to convert the objective functions to:

$$t = \sum_i \sum_j \sum_m \sum_n (b_{imn} + s_{ijm} + e_{im} + h_{im} \sum_{\underline{i}} w_{\underline{im}} \sum_{\underline{i}} \sum_{\underline{j}} X_{\underline{ijmn}}) X_{ijmn}$$

$$t_n = \sum_i \sum_j \sum_m (b_{imn} + s_{ijm} + e_{im} + h_{im} \sum_{\underline{i}} w_{\underline{im}} \sum_{\underline{i}} \sum_{\underline{j}} X_{\underline{ijmn}}) X_{ijmn}$$

One can immediately see that the objective functions are quadratic in X. Fortunately, several methods have been devised for solving quadratic programming problems.

Solution

The most efficient quadratic programming technique is Dantzig's Simplex algorithm for quadratic programming. Dantzig's algorithm attacks the problem of maximizing:

$$A'X - \frac{1}{2} X'BX$$

X = n - dimensional vector

$A = 1 \times n$ matrix

$B = n \times n$ matrix

subject to:

$$C'X \leq D$$

$C' = n \times k$ matrix

$D = 1 \times k$ matrix

and:

$$X \geq 0$$

This is, of course, equilavent to minimizing:

$$- A'X + \frac{1}{2} X'BX$$

subject to:

$$C'X \leq D$$

and $$X \geq 0$$

Note that there is no provision for equality constraints, such as exist in the network transportation model ($a_{imn} = \sum_m X_{ijmn}$). This being the case, we are forced to convert the problem to one containing only inequality constraints.

The obvious way to accomplish this purpose is to rewrite the model's equality constraints as a double set of inequalities:

change $a_{ijn} = \sum_m X_{ijmn}$ for all i, j, n

to $a_{ijn} \geq \sum_m X_{ijmn}$ for all i, j, n

$a_{ijn} \leq \sum_m X_{ijmn}$ for all i, j, n

However, there is a major difficulty associated with this process. The use of Dantzig's algorithm requires a Simplex tableau, and the above procedure leads to a rather large tableau.

Assume that the network model contains K port constraints, I cargo types, J destinations, M ports, and N sources. In the 'superior agency' formulation, there are then IJMN variables and IJN equality constraints. The above conversion produces 2IJN inequality constraints in addition to the original K port constraints. The Simplex tableau has approximately

$$2(\text{number of variables} + \text{number of inequalities})^2$$

elements. Thus, the model's tableau has about

$$2(IJMN + 2IJN + K)^2$$

elements.

There is, however, another way to eliminate the equality constraints. They can be written as:

$$X_{ijMn} = a_{ijn} - \sum_{m}^{M-1} X_{ijmn} \qquad \text{for } i = 1 \text{ to } I, \quad j = 1 \text{ to } J, \quad n = 1 \text{ to } N$$

Using standard algebraic techniques, these equalities can be used to eliminate variables from the objective function. One merely writes the RHS of the above equation everywhere X_{ijMn} appears in the objective function (and in port constraints). This eliminates IJN variables, leaving IJN(M-1). However, there is now no guarantee that X_{ijMn} will remain positive. This guarantee can be provided by introducing IJN inequalities of the form:

$$a_{ijn} \geq \sum_{m}^{M-1} X_{ijmn} \qquad i = 1 \text{ to } I, \quad j = 1 \text{ to } J, \quad n = 1 \text{ to } N$$

The model's tableau now contains

$$2(IJN(M-1) + IJN + K)^2$$

elements. This is

$$(8M + 8)(IJN)^2 + 8IJNK$$

fewer elements than the first formulation. This reduction of tableau size is considerable when large systems are modeled. The necessary modifications of the objective functions are presented in Appendix I. Modification of the constraint set is straightforward, merely requiring the substitution of $a_{ijn} - \sum_{m}^{M-1}$ for X_{ijMn} wherever it appears.

This conversion of the objective functions and constraint set essentially eliminates all variables of the form X_{ijMn}. Thus, the cargo routing schedule produced by the Simplex algorithm does not explicitly contain the cargo flows through the M^{th} port in the model. It is necessary to generate these values from the Simplex results using the equality constraints:

$$X_{ijMn} = a_{ijn} - \sum_{m}^{M-1} X_{ijmn} \qquad \begin{array}{l} \text{for } i = 1 \text{ to } I \\ j = 1 \text{ to } J \\ n = 1 \text{ to } N \end{array}$$

Use of the variable subscripts i, j, m, and n is rather awkward in the matrix formulation. Given in Appendix I is a general formula for converting the quadruple subscript notation to a single subscript notation. This formula is such that every X_{ijmn} is uniquely renamed X_k. Henceforth, individual cargo flow rates are referred to as X_k, $k = 1, 2, \ldots IJN(M-1)$, and the vector whose elements are X_k is referred to as $\underline{X}$.

The equations describing the seaport transportation model are now in the form:

$$\min t = g - A'\underline{X} + \frac{1}{2}\underline{X}'B\underline{X}$$

$$C'\underline{X} \leq D$$

$$X \geq 0$$

The constant term g appearing in the objective function can, of course, be ignored during the maximization procedure.

Dantzig's algorithm requires that the quadratic matrix B be positive semidefinite (convex). This requirement excludes problems possessing local maxima, guaranteeing that the algorithm will converge to a global maxima. Given in Appendix II is a proof that, provided there are two or more overseas destinations in the model, the B matrix generated by the model is always positive semidefinite. Dantzig's technique begins by converting the inequalities of the constraint set to equalities through the addition of artificial variables:

$$C'\underline{X} + I\underline{Y} = D$$

In the superior agency formulation there are now IJN(M-1) elements in X and IJN+K artificial variables in Y. Define a new vector, $\underline{Z}$, of dimension IJN(M-1) + IJN + K:

$$\underline{Z} = (\underline{X}'\underline{Y}')' = (z_1, z_2, \ldots, z_n)'$$

Define two new vectors, $\underline{V}$ and $\underline{W}$, with the same dimensions as $\underline{X}$ and $\underline{Y}$, respectively:

$$\underline{V} = (v_1, v_2, v_3, \ldots, v_n)' \qquad n = IJN(M-1)$$

$$\underline{W} = (w_1, w_2, w_3, \ldots, w_n)' \qquad n = IJN + K$$

These vectors can be conjoined to form another vector analogous to $\underline{Z}$:

$$\underline{U} = (\underline{V}'\underline{W}') = (u_1, u_2, \ldots, u_n) \qquad n = IJN(M-1) + IJN + K$$

With the above definitions, the Kuhn-Tucker theorem[1] for quadratic programming can be stated as: the vector $\underline{Z}$ is a

[1]Boot, Quadratic Programming, Rand McNally, 1964, p. 51.

solution to the quadratic programming problem if and only if $\underline{Z}$ is non-negative,

$$\underline{Z} = (\underline{X}'\underline{Y}')' \geq 0$$

and if there exists a vector $\underline{U}$ of non-negative elements,

$$\underline{U} = (\underline{V}'\underline{W}')' \geq 0$$

such that

$$\underline{U}'\underline{Z} = 0$$

and such that

$$\begin{bmatrix} -B & 0 & I & -C \\ C' & I & 0 & 0 \end{bmatrix} \begin{bmatrix} \underline{X} \\ \underline{Y} \\ \underline{V} \\ \underline{W} \end{bmatrix} = \begin{bmatrix} -A \\ D \end{bmatrix}$$

While searching for a $\underline{U}$ and $\underline{Z}$ satisfying all the above conditions, Dantzig's algorithm insures that the first and last conditions are met. That is, at each iteration, the algorithm systematically modifies the elements of $\underline{U}$ and $\underline{Z}$ in such a way that satisfaction of the first and last conditions is insured.

The third condition, $\underline{U}'\underline{Z} = 0$, indicates that in the optimal solution, at least IJMN+K of the 2[IJMN+K] elements in $\underline{U}$ and $\underline{Z}$ are zero. Indeed, the Simplex algorithm insures that only IJMN+K elements are non-zero, but it does not, at all stages, insure that $\underline{U}'\underline{Z} = 0$. Referring to non-zero elements as basic variables, the condition that $\underline{U}'\underline{Z} = 0$ implies that whenever an element of $\underline{U}$ is basic, the corresponding element of $\underline{Z}$ is zero, and vice versa. During the operation of the Simplex algorithm, it may happen that, at most, both elements of one set of corresponding $\underline{U}$ and $\underline{Z}$ variables are basic, violating $\underline{U}'\underline{Z} = 0$. This situation is referred to as a 'nonstandard tableau'. If $\underline{U}'\underline{Z} = 0$ is satisfied, the situation is referred to as a 'standard tableau'. The rules of the algorithm are such that when faced with a nonstandard tableau, it attempts to convert it to a standard tableau.

The third condition, $\underline{U} \geq 0$, is violated at all stages of the algorithm, except when the optimal solution is achieved.

The algorithm starts off with a solution satisfying the first, third, and fourth Kuhn-Tucker conditions. If D is positive, such a solution is immediately apparent. Setting $\underline{X} = \underline{W} = 0$ converts the fourth condition to:

$$\begin{bmatrix} 0 & I \\ I & 0 \end{bmatrix} \begin{bmatrix} \underline{Y} \\ \underline{V} \end{bmatrix} = \begin{bmatrix} -A \\ D \end{bmatrix}$$

which yields:

$$\underline{Y} = -A$$
$$\underline{V} = D$$

Such will be the case when the port constraints are all capacity constraints and no constraints are applied to the M^{th} port, for example. If D is not positive, it may be the case that a basic feasible solution can be achieved through inspection. If the problem fails to yield to this, there exists an algorithm devised by Wolfe[1,2] capable of finding a suitable

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[1]P. Wolfe, "The Simplex Method for Quadratic Programming," Econometrica, Vol. 27, 1959, pp. 382-398.

[2]Boot, Quadratic Programming, Rand McNally, 1964, p. 198.

solution. For simplicity, it is assumed that D is positive. This being the case, the initial standard Simplex tableau can be immediately written:

Basic Variables	Value Basic Variables	X (Z)	Y (Z)	V (U)	W (U)
V	-A	-B	0	I	-C
Y	D	C'	I	0	0

The rules for operating on the tableau are different for standard and nonstandard tableaus. For notational convenience, refer to the elements of the 'Value Basic Variable' column as p_i, i = 1, 2, ..., IJNM+K. The rules for a standard tableau are then:

> Adding a variable to the basis: If the tableau is in standard form, that non-basic Z-variable (z_h) should enter the basis whose corresponding U variable (u_h) has (in absolute value) the largest negative p_i. Refer to the elements of the column beneath z_h as s_i, i = 1, 2, ..., IJMN+K.
>
> Deleting a variable from the basis: If the tableau is in standard form, consider the ratios p_i/s_i for all basic Z-variables and for u_h. Delete the variable corresponding to the smallest positive ratio.

To apply these rules, simply scan down the 'Value Basic Variables' column and select the most negative entry. This entry is associated with a U-variable, u_h (only U variables can be negative). The Z-variable associated with u_h, z_h, should enter the basis. Denote the elements of the column beneath z_h

as s_i, i = 1, 2, ..., IJMN+K. Now consider the ratios p_i/s_i for all the basic $\underline{Z}$ variables and for u_h. Select that row for which this ratio is the smallest, ignoring negative and zero ratios. The intersection of this row and the z_h column is the pivot element.

The rules for a nonstandard tableau are:

Adding a variable to the basis: If the tableau is in nonstandard form, write (z_k,u_k) for the non-basic pair, then u_k should enter the basis. Refer to the elements of the column beneath u_k as s_i, i = 1, 2, ..., IJMN+K.

Deleting a variable from the basis: If the tableau is in nonstandard form, write (z_h,u_h) for the basic pair. Consider the ratios p_i/s_i for all basic $\underline{Z}$ variables and for u_h. Delete the variable corresponding to the smallest positive ratio.

To apply these rules, first determine which pair of corresponding $\underline{Z}$ and $\underline{U}$ variables has both elements non-basic. The u_k of this pair should enter the basis. Denote the column beneath it as s_i, i = 1, 2, ..., IJMN+K. Also determine which pair of variables has both elements basic, and call that pair (z_h,u_h). Now consider all the ratios p_i/s_i for all basic $\underline{Z}$ variables and for u_h. Select that row producing the smallest positive ratio, ignoring negative and zero ratios. The intersection of this row and the u_k column is the pivot element.

Now that the pivot element has been selected, the algorithm's rules are identical for standard and nonstandard tableaux. The following rules describe a pivoting operation similar to that used in linear programming.

1) Divide the pivot element's row by the value of the pivot element, thereby setting the pivot element's value to 1.

2) Add and subtract multiples of the pivot element's row to all other rows in such a way as to set to zero all elements in the pivot element's column (except for itself).

3) In the Basic Variable column, delete the variable chosen by the previous rules and insert the 'variable to be added to the basis' in its place.

The iteration is now complete, and a new Simplex tableau has been generated. The above rules are such as to insure that the new set of basic variables the first and fourth Kuhn-Tucker conditions. If the tableau is in nonstandard form ($\underline{U}'\underline{Z} \neq 0$) or if not all basic $\underline{U}$ variables are non-negative ($\underline{U}' \geq 0$), then another iteration is required. If, however, the conditions $\underline{U}'\underline{Z} = 0$ and $\underline{U}' \geq 0$ are satisfied, then all four Kuhn-Tucker conditions are satisfied. The optimal cargo flow rates are then contained in the Value Basic Variables column of the Simplex tableau.

The cargo flow rates for the M^{th} port do not appear explicitly in the objective function. It remains to use the equality constraints to find these values:

$$X_{ijMn} = a_{ijn} - \sum_{m}^{M-1} X_{ijmn}$$

The above discussion tacitly assumes the problem is in the superior agency formulation. Solution of the single source formulation proceeds along identical lines, except that the objective function is as presented in the second section of Appendix I. A sample problem, including all of its tableaux, is presented in Appendix III.

Summary

The seaport transportation network model described in this report can be used to effectively represent the transportation network responsible for transferring goods from the heartland of one country to the seaports of another. By solving the quadratic programming problem associated with the model, the minimum cost routing schedule for all cargo in the system can be found. Assuming that the various cost coefficients and port constraints in the model accurately reflect reality, the final routing schedule will approximate the cargo flows found in the actual system. The effects of modification of the real system can be found by appropriately adjusting the model and either using the sensitivity analysis techniques of quadratic programming[1] or solving the adjusted problem.

This model formulation contains a mode of cargo flow interaction not found in linear programming formulations. This interaction is supplied by the concept of port congestion. Although an increase in shipping cost due to heavy usage of port facilities cannot be easily represented in a linear model, it is the very heart of this quadratic model. This fact opens the possibility of, for instance, predetermining the responses

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[1]Boot, Quadratic Programming, McGraw-Hill, 1964, Ch. 8.

of a transportation system's cost structure to overall changes in the rate of cargo export or to modifications of port capacities and costs. Such added flexibility should enable researchers to more effectively analyze the relationships governing seaport transportation networks.

There is, however, one overriding factor governing the usefulness of this model: the magnitude of the Simplex tableau. As noted before, the tableau contains approximately

$$2(IJMN+K)^2$$

elements. A model containing, for instance, four ports, four cargo types, four overseas destinations, four sources and sixteen constraints generates a tableau with 73,984 elements. This is approaching a reasonable limit for the size of problem a medium capacity computer can handle. A $6 \times 6 \times 6 \times 6 \times 6$ problem would require a computer capable of handling nearly two million elements. Solution of such a problem would require an exorbitant execution time, and would have prohibitive price tag.

DERIVATIONS OF MATRIX FORMS

Introduction

This appendix details the derivations of the matrix forms of the shipping cost equations. Two forms are presented: that for which the total cost is the cost incurred by all inland sources, and that for which the total cost is only the cost incurred by the n^{th} inland source. The former derivation produces the 'superior agency' formulation referred to in the text, while the latter results in the 'one source' formulation.

Both derivations begin by combining the shipping cost and port congestion equations. The constraint equations that provide for demand satisfaction are then used to eliminate all variables associated with one of the ports. The resultant expressions of the total shipping cost are then rearranged into standard, quadratic matrix form.

In the following equations, except where noted, all summations run from one to the upper bound of the index:

$$\sum_{i=1}^{I} \text{ is written as } \sum_{i}$$

Superior Agency Derivation

It should be noted that there are I cargo types, N inland sources, J overseas destinations, and M ports in the model. Thus, we initially have IJMN variables. Using the IJN equality constraints, we reduce the number of variables to IJN(M-1).

Initial equations:

$$y_{im} = \sum_{n} \sum_{j} x_{ijmn}$$

$$w_m = \sum_{i} w_{im} y_{im}$$

$$c_{im} = e_{im} + h_{im} w_m$$

$$x_{ijMn} = a_{ijn} - \sum_{m}^{M-1} x_{ijmn}$$

$$t = \sum_{i} \sum_{j} \sum_{m} \sum_{n} (b_{imn} + s_{ijm} + c_{im}) x_{ijmn}$$

w_{im}, e_{im}, h_{im}, a_{ijn}, b_{imn}, s_{ijm} constants

$$t = \sum_{i} \sum_{j} \sum_{m} \sum_{n} (b_{imn} + s_{ijm} + e_{im} + h_{im} \sum_{\underline{i}} w_{\underline{i}m} \sum_{\underline{n}} \sum_{\underline{j}} x_{\underline{i}\underline{j}m\underline{n}}) x_{ijmn}$$

$$t = \sum_{i} \sum_{j} \sum_{m} \sum_{n} (b_{imn} + s_{ijm} + e_{im}) x_{ijmn} + \sum_{i} \sum_{j} \sum_{m} \sum_{n} \left\{ h_{im} \sum_{\underline{i}} w_{\underline{i}m} \sum_{\underline{n}} \sum_{\underline{j}} x_{\underline{i}\underline{j}m\underline{n}} \right\} x_{ijmn}$$

Working on the first term:

$$\sum_i \sum_j \sum_m \sum_n (b_{imn} + s_{ijm} + e_{im})x_{ijmn} =$$

$$\sum_i \sum_j \sum_n \left\{ \sum_m^{M-1} (b_{imn} + s_{ijm} + e_{im})x_{ijmn} + (b_{iMn} + s_{ijM} + e_{iM})x_{ijMn} \right\}$$

$$\sum_i \sum_j \sum_n \left\{ \sum_m^{M-1} (b_{imn} + s_{ijm} + e_{im})x_{ijmn} + (b_{iMn} + s_{ijM} + e_{iM})(a_{ijn} - \sum_m^{M-1} x_{ijmn}) \right\}$$

$$\sum_i \sum_j \sum_n \left\{ a_{ijn}(b_{iMn} + s_{ijM} + e_{iM}) + \sum_m^{M-1} (b_{imn} + s_{ijm} + e_{im} - b_{iMn} - s_{ijM} - e_{iM})x_{ijmn} \right\}$$

$$\sum_i \sum_j \sum_n \{a_{ijn}(b_{iMn} + s_{ijM} + e_{iM}) + \sum_i \sum_j \sum_m^{M-1} \sum_n \{b_{imn} + s_{ijm} + e_{im} - b_{iMn} - s_{ijM} - e_{iM})x_{ijmn}\}$$

Working on the second term:

$$\sum_i \sum_j \sum_m \sum_n \{h_{im} \sum_{\underline{i}} w_{\underline{i}m} \sum_{\underline{n}} \sum_{\underline{j}} x_{\underline{i}\underline{j}m\underline{n}}\}x_{ijmn} = \sum_i \sum_j \sum_m \sum_n \left\{ \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} h_{im} w_{\underline{i}m} x_{\underline{i}\underline{j}m\underline{n}} x_{ijmn} \right\}$$

$$= \sum_i \sum_j \sum_n \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} \left\{ \sum_m^{M-1} h_{im} w_{\underline{i}m} x_{\underline{i}\underline{j}m\underline{n}} x_{ijmn} + h_{iM} w_{\underline{i}M} x_{\underline{i}\underline{j}M\underline{n}} x_{ijMn} \right\}$$

$$= \sum_i \sum_j \sum_n \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} \left\{ \sum_m^{M-1} h_{im} w_{\underline{i}m} x_{\underline{i}\underline{j}m\underline{n}} x_{ijmn} + h_{iM} w_{\underline{i}M} (a_{\underline{i}\underline{j}\underline{n}} - \sum_m^{M-1} x_{ijmn})(a_{ijn} - \sum_m^{M-1} x_{ijmn}) \right\}$$

$$= \sum_{i}\sum_{j}\sum_{n}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}}\left\{\sum_{m}^{M-1} h_{im}w_{\underline{i}\underline{m}}x_{\underline{i}\underline{j}m\underline{n}}x_{ijmn} + h_{iM}w_{\underline{i}M}a_{\underline{i}\underline{j}\underline{n}}a_{ijn} - h_{iM}w_{\underline{i}M}a_{\underline{i}\underline{j}\underline{n}}\sum_{m}^{M-1} x_{ijmn}\right.$$

$$\left. - h_{iM}w_{\underline{i}M}a_{\underline{i}\underline{j}\underline{n}}\sum_{m}^{M-1} x_{\underline{i}\underline{j}m\underline{n}} + h_{iM}w_{\underline{i}M}\left(\sum_{m}^{M-1} x_{\underline{i}\underline{j}m\underline{n}}\right)\left(\sum_{m}^{M-1} x_{ijmn}\right)\right\}$$

$$= \sum_{i}\sum_{j}\sum_{n}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}} h_{iM}w_{\underline{i}M}a_{\underline{i}\underline{j}\underline{n}}a_{ijn} - \sum_{i}\sum_{j}\sum_{n}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}} h_{iM}w_{\underline{i}M}\left\{\sum_{m}^{M-1} a_{\underline{i}\underline{j}\underline{n}}x_{ijmn} + \sum_{m}^{M-1} a_{ijn}x_{\underline{i}\underline{j}m\underline{n}}\right\}$$

$$+ \sum_{i}\sum_{j}\sum_{n}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}}\left\{\sum_{m}^{M-1} h_{im}w_{\underline{i}m}x_{\underline{i}\underline{j}m\underline{n}}x_{ijmn} + h_{iM}w_{\underline{i}M}\left(\sum_{m}^{M-1} x_{\underline{i}\underline{j}m\underline{n}}\right)\left(\sum_{m}^{M-1} x_{ijmn}\right)\right\}$$

Working on the second term above:

$$\sum_{i}\sum_{j}\sum_{n}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}} h_{iM}w_{\underline{i}M}\left\{\sum_{m}^{M-1} a_{\underline{i}\underline{j}\underline{n}}x_{ijmn} + \sum_{m}^{M-1} a_{ijn}x_{\underline{i}\underline{j}m\underline{n}}\right\}$$

$$= \sum_{i}\sum_{j}\sum_{n}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}}\sum_{m}^{M-1}\left\{h_{iM}w_{\underline{i}M}a_{\underline{i}\underline{j}\underline{n}}x_{ijmn}\right\} + \sum_{i}\sum_{j}\sum_{n}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}}\sum_{\underline{m}}^{M-1}\left\{h_{iM}w_{\underline{i}M}a_{ijn}x_{\underline{i}\underline{j}\underline{m}\underline{n}}\right\}$$

$$= \sum_{i}\sum_{j}\sum_{n}\sum_{m}^{M-1}\left\{\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}} h_{iM}w_{\underline{i}M}a_{\underline{i}\underline{j}\underline{n}}\right\}x_{ijmn} + \sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}}\sum_{\underline{m}}^{M-1}\left\{\sum_{i}\sum_{j}\sum_{n} h_{iM}w_{\underline{i}M}a_{ijn}\right\}x_{\underline{i}\underline{j}\underline{m}\underline{n}}$$

$$= \sum_{i}\sum_{j}\sum_{n}\sum_{m}^{M-1}\left\{\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}} h_{iM}w_{\underline{i}M}a_{\underline{i}\underline{j}\underline{n}}\right\}x_{ijmn} + \sum_{i}\sum_{j}\sum_{n}\sum_{m}^{M-1}\left\{\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}} h_{\underline{i}M}w_{iM}a_{\underline{i}\underline{j}\underline{n}}\right\}x_{ijmn}$$

$$= \sum_{i}\sum_{j}\sum_{n}\sum_{m}^{M-1}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}}\left\{(h_{iM}w_{\underline{i}M}a_{\underline{i}\underline{j}\underline{n}} + h_{\underline{i}M}w_{iM}a_{\underline{i}\underline{j}\underline{n}})\right\}x_{ijmn}$$

Working on the third term:

$$\sum_i \sum_j \sum_n \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} \left\{ \sum_m^{M-1} h_{im} w_{\underline{i}m} x_{\underline{i}\underline{j}m\underline{n}} x_{ijmn} + h_{iM} w_{\underline{i}M} \left(\sum_m^{M-1} x_{\underline{i}\underline{j}m\underline{n}} \right) \left(\sum_m^{M-1} x_{ijmn} \right) \right\}$$

$$= \sum_i \sum_j \sum_n \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} \left\{ \sum_{\underline{m}}^{M-1} \sum_m^{M-1} d_{m\underline{m}} h_{im} w_{\underline{i}m} x_{\underline{i}\underline{j}\underline{m}\underline{n}} x_{ijmn} + \sum_{\underline{m}}^{M-1} \sum_m^{M-1} h_{iM} w_{\underline{i}M} x_{\underline{i}\underline{j}\underline{m}\underline{n}} x_{ijmn} \right\}$$

$$d_{m\underline{m}} = \begin{cases} 1 \text{ if } m = \underline{m} \\ 0 \text{ if } m \neq \underline{m} \end{cases}$$

$$= \sum_i \sum_j \sum_n \sum_m \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} \left\{ \sum_{\underline{m}}^{M-1} \sum_m^{M-1} (d_{m\underline{m}} h_{im} w_{\underline{i}m} + h_{iM} w_{\underline{i}M}) x_{\underline{i}\underline{j}\underline{m}\underline{n}} x_{ijmn} \right\}$$

$$= \sum_i \sum_j \sum_n \sum_m^{M-1} \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} \sum_{\underline{m}}^{M-1} (d_{m\underline{m}} h_{im} w_{\underline{i}m} + h_{iM} w_{\underline{i}M}) x_{\underline{i}\underline{j}\underline{m}\underline{n}} x_{ijmn}$$

Combining the above terms:

$$t = \sum_i \sum_j \sum_n \left\{ a_{ijn} (b_{iMn} + s_{ijM} + e_{iM} + \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} h_{iM} w_{\underline{i}M} a_{\underline{i}\underline{j}\underline{n}}) \right\}$$

$$+ \sum_i \sum_j \sum_n \sum_m^{M-1} \left\{ b_{imn} + s_{ijm} + e_{im} - b_{iMn} - s_{ijM} - e_{iM} - \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} a_{\underline{i}\underline{j}\underline{n}} (h_{iM} w_{\underline{i}M} + h_{\underline{i}M} w_{iM}) \right\} x_{ijmn}$$

$$+ \sum_i \sum_j \sum_n \sum_m^{M-1} \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} \sum_{\underline{m}}^{M-1} (d_{m\underline{m}} h_{im} w_{\underline{i}m} + h_{iM} w_{\underline{i}M}) x_{\underline{i}\underline{j}\underline{m}\underline{n}} x_{ijmn}$$

Set $k = (n-1)(M-1)IJ + (i-1)(M-1)J + (m-1)J + j$

This maps each set of ijmn into a unique k.

$$t = \sum_i \sum_j \sum_n \left\{ a_{ijn} \left(b_{iMn} + s_{ijM} + e_{iM} + \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} h_{iM} w_{\underline{i}M} a_{\underline{i}\underline{j}\underline{n}} \right) \right\}$$

$$+ \sum_k \left\{ b_{imn} + s_{ijm} + e_{im} - b_{iMn} - s_{ijM} - e_{iM} - \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} a_{\underline{i}\underline{j}\underline{n}} \left(h_{iM} w_{\underline{i}M} + h_{\underline{i}M} w_{iM} \right) \right\} x_k$$

$$+ \sum_k \sum_{\underline{k}} \left(d_{m\underline{m}} h_{im} w_{\underline{i}m} + h_{iM} w_{\underline{i}M} \right) x_k x_{\underline{k}}$$

Considering the set of variables $\{x_k\}$ as a vector of dimension IJN(M-1), we can rewrite the above equation in matrix form:

$$t = g - AX + \frac{1}{2} X'BX$$

$$X' = [x_1, x_2, x_3, \ldots, x_n] \qquad n = IJN(M-1)$$

$$g = \sum_i \sum_j \sum_n \left\{ a_{ijn} \left(b_{iMn} + s_{ijM} + e_{iM} + \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} h_{iM} w_{\underline{i}M} a_{\underline{i}\underline{j}\underline{n}} \right) \right\}$$

$$a_k = -b_{imn} - s_{ijm} - e_{im} + b_{iMn} + s_{ijM} + e_{iM} + \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} a_{\underline{i}\underline{j}\underline{n}} \left(h_{iM} w_{\underline{i}M} + h_{\underline{i}M} w_{iM} \right)$$

$$b_{k\underline{k}} = d_{m\underline{m}} \left(h_{im} w_{\underline{i}m} + h_{\underline{i}m} w_{i\underline{m}} \right) + h_{iM} w_{\underline{i}M} + h_{\underline{i}M} w_{iM}$$

Single Source Derivation

The model equations contain IJMN variables. However, in the single source formulation, only those variables associated with the n^{th} source can be modified in attempts to minimize the total cost. Thus, those variables, $X_{ij m\underline{n}}$ with $\underline{n} \neq n$, must be treated as constants in the minimization algorithm. Only those variables, $X_{ij m\underline{n}}$ with $\underline{n} = n$ are open to change. One should bear in mind this distinction while following the derivation.

This formulation initially contains IJM variables. After the use of the IJ equality constraints, only IJ(M-1) variables remain.

Initial equations:

$$y_{im} = \sum_{n} \sum_{j} x_{ijmn}$$

$$w_{m} = \sum_{i} w_{im} y_{im}$$

$$c_{im} = e_{im} + h_{im} w_{m}$$

$$x_{ijMn} = a_{ijn} - \sum_{m}^{M-1} x_{ijmn}$$

$$t_{n} = \sum_{i} \sum_{j} \sum_{m}^{M-1} (b_{imn} + s_{ijm} + c_{im}) x_{ijmn}$$

w_{im}, e_{im}, h_{im}, a_{ijn}, b_{imn}, s_{ijm} constants

$$t_{n} = \sum_{i} \sum_{j} \sum_{m}^{M-1} (b_{imn} + s_{ijm} + e_{im} + h_{im} \sum_{\underline{i}} w_{\underline{i}m} \sum_{\underline{n}} \sum_{\underline{j}} x_{\underline{i}\underline{j}m\underline{n}}) x_{ijmn}$$

$$t_{n} = \sum_{i} \sum_{j} \sum_{m}^{M-1} (b_{imn} + s_{ijm} + e_{im}) x_{ijmn} + \sum_{i} \sum_{j} \sum_{m}^{M-1} \left\{ h_{im} \sum_{\underline{i}} w_{\underline{i}m} \sum_{\underline{n}} \sum_{\underline{j}} x_{\underline{i}\underline{j}m\underline{n}} \right\} x_{ijmn}$$

Working on the first term:

$$\sum_i \sum_j \sum_m (b_{imn} + s_{ijm} + e_{im})x_{ijmn}$$

$$= \sum_i \sum_j \left\{ \sum_m^{M-1} (b_{imn} + s_{ijm} + e_{im})x_{ijmn} + (b_{iMn} + s_{ijM} + e_{iM})x_{ijMn} \right\}$$

$$= \sum_i \sum_j \left\{ \sum_m^{M-1} (b_{imn} + s_{ijm} + e_{im})x_{ijmn} + (b_{iMn} + s_{ijM} + e_{iM})(a_{ijn} - \sum_m^{M-1} x_{ijmn}) \right\}$$

$$= \sum_i \sum_j \left\{ (b_{iMn} + s_{ijM} + e_{iM})a_{ijn} + \sum_m^{M-1} (b_{imn} + s_{ijm} + e_{im} - b_{iMn} - s_{ijM} - e_{iM})x_{ijmn} \right\}$$

Working on the second term:

$$\sum_i \sum_j \sum_m^{M-1} \{h_{im} \sum_{\underline{i}} w_{\underline{i}m} \sum_{\underline{n}} \sum_{\underline{j}} x_{\underline{i}\underline{j}m\underline{n}}\}x_{ijmn} = \sum_i \sum_j \sum_{\underline{i}} \sum_{\underline{n}} \sum_{\underline{j}} \left\{ \sum_m^{M-1} h_{im}w_{\underline{i}m}x_{\underline{i}\underline{j}m\underline{n}}x_{ijmn} \right\}$$

$$= \sum_i \sum_j \sum_{\underline{i}} \sum_{\underline{n}} \sum_{\underline{j}} \left\{ \sum_m^{M-1} h_{im}w_{\underline{i}m}x_{\underline{i}\underline{j}m\underline{n}}x_{ijmn} + h_{iM}w_{\underline{i}M}x_{\underline{i}\underline{j}M\underline{n}}x_{ijMn} \right\}$$

$$= \sum_i \sum_j \sum_{\underline{i}} \sum_{\underline{n}} \sum_{\underline{j}} \left\{ \sum_m^{M-1} h_{im}w_{\underline{i}m}x_{\underline{i}\underline{j}m\underline{n}}x_{ijmn} + h_{iM}w_{\underline{i}M}(a_{\underline{i}\underline{j}\underline{n}} - \sum_m^{M-1} x_{\underline{i}\underline{j}m\underline{n}})(a_{ijn} - \sum_m^{M-1} x_{ijmn}) \right\}$$

$$= \sum_i \sum_j \sum_{\underline{i}} \sum_{\underline{n}} \sum_{\underline{j}} \left\{ \sum_m^{M-1} h_{im}w_{\underline{i}m}x_{\underline{i}\underline{j}m\underline{n}}x_{ijmn} + h_{iM}w_{\underline{i}M}a_{\underline{i}\underline{j}\underline{n}}a_{ijn} - h_{iM}w_{\underline{i}M}a_{ijn} \sum_m^{M-1} x_{\underline{i}\underline{j}m\underline{n}} \right.$$

$$\left. - h_{iM}w_{\underline{i}M}a_{\underline{i}\underline{j}\underline{n}} \sum_m^{M-1} x_{ijmn} + h_{iM}w_{\underline{i}M}\left(\sum_m^{M-1} x_{\underline{i}\underline{j}m\underline{n}}\right)\left(\sum_m^{M-1} x_{ijmn}\right) \right\}$$

Working on the third and fourth terms:

$$-\sum_{i}\sum_{j}\sum_{\underline{i}}\sum_{\underline{n}}\sum_{\underline{j}}\left\{h_{iM}w_{\underline{i}M}a_{ijn}\sum_{m}^{M-1}x_{\underline{i}\underline{j}m\underline{n}} + h_{iM}w_{\underline{i}M}a_{\underline{i}\underline{j}\underline{n}}\sum_{m}^{M-1}x_{ijmn}\right\}$$

$$= -\sum_{i}\sum_{j}\sum_{\underline{i}}\sum_{\underline{n}}\sum_{\underline{j}}\sum_{m}^{M-1} g_{n\underline{n}}h_{iM}w_{\underline{i}M}a_{ijn}x_{\underline{i}\underline{j}mn} - \sum_{i}\sum_{j}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{m}^{M-1} h_{iM}w_{\underline{i}M}a_{ijn}x_{\underline{i}\underline{j}mn}$$

$$- \sum_{i}\sum_{j}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}}\sum_{m}^{M-1} h_{iM}w_{\underline{i}M}a_{\underline{i}\underline{j}\underline{n}}x_{ijmn}$$

$$\text{where} \quad g_{n\underline{n}} = \begin{cases} 0 \text{ if } n = \underline{n} \\ 1 \text{ if } n \neq \underline{n} \end{cases}$$

$$= -\sum_{i}\sum_{j}\sum_{m}^{M-1}\sum_{\underline{i}}\sum_{\underline{j}} h_{\underline{i}M}w_{iM}a_{\underline{i}\underline{j}n}x_{ijmn} - \sum_{i}\sum_{j}\sum_{m}^{M-1}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}} h_{iM}w_{\underline{i}M}a_{\underline{i}\underline{j}\underline{n}}x_{ijmn}$$

$$- \sum_{i}\sum_{j}\sum_{m}^{M-1}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}} g_{n\underline{n}}h_{iM}w_{\underline{i}M}a_{ijn}x_{\underline{i}\underline{j}m\underline{n}}$$

$$= -\sum_{i}\sum_{j}\sum_{m}^{M-1}\left\{\sum_{\underline{i}}\sum_{\underline{j}}(h_{\underline{i}M}w_{iM}a_{\underline{i}\underline{j}n} + \sum_{\underline{n}}h_{iM}w_{\underline{i}M}a_{\underline{i}\underline{j}\underline{n}})\right\} x_{ijmn} - \sum_{i}\sum_{j}\sum_{m}^{M-1}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{n}} g_{n\underline{n}}h_{iM}w_{\underline{i}M}a_{ijn}x_{\underline{i}\underline{j}m\underline{n}}$$

Working on the first and fifth terms:

$$\sum_{i}\sum_{j}\sum_{\underline{i}}\sum_{\underline{n}}\sum_{\underline{j}}\left\{\sum_{m}^{M-1} h_{im}w_{\underline{i}m}x_{\underline{i}\underline{j}m\underline{n}}x_{ijmn} + h_{iM}w_{\underline{i}M}\sum_{m}^{M-1} x_{\underline{i}\underline{j}m\underline{n}}\sum_{m}^{M-1} x_{ijmn}\right\}$$

$$= \sum_{i}\sum_{j}\sum_{\underline{i}}\sum_{\underline{n}}\sum_{\underline{j}}\left\{\sum_{\underline{m}}^{M-1}\sum_{m}^{M-1} p_{m\underline{m}}h_{im}w_{\underline{i}m}x_{\underline{i}\underline{j}\underline{m}\underline{n}}x_{ijmn} + h_{iM}w_{\underline{i}M}\sum_{\underline{m}}^{M-1}\sum_{m}^{M-1} x_{\underline{i}\underline{j}\underline{m}\underline{n}}x_{ijmn}\right\}$$

$$p_{m\underline{m}} = \begin{cases} 1 \text{ if } m = \underline{m} \\ 0 \text{ if } m \neq \underline{m} \end{cases}$$

$$= \sum_{i}\sum_{j}\sum_{m}^{M-1}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{m}}^{M-1}\left\{\sum_{\underline{n}}(p_{m\underline{m}}h_{im}w_{\underline{i}m} + h_{iM}w_{\underline{i}M})x_{\underline{i}\underline{j}\underline{m}\underline{n}}x_{ijmn}\right\}$$

$$= \sum_{i}\sum_{j}\sum_{m}^{M-1}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{m}}^{M-1}\left\{(p_{m\underline{m}}h_{im}w_{\underline{i}m} + h_{iM}w_{\underline{i}M})(x_{\underline{i}\underline{j}\underline{m}n}x_{ijmn} + \sum_{\underline{n}}t_{n\underline{n}}x_{\underline{i}\underline{j}\underline{m}\underline{n}}x_{ijmn})\right\}$$

$$t_{n\underline{n}} = \begin{cases} 0 \text{ if } n = \underline{n} \\ 1 \text{ if } n \neq \underline{n} \end{cases}$$

$$= \sum_{i}\sum_{j}\sum_{m}^{M-1}\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{m}}^{M-1}\left\{p_{m\underline{m}}h_{im}w_{\underline{i}m} + h_{iM}w_{\underline{i}M}\right\} x_{\underline{i}\underline{j}\underline{m}n}x_{ijmn}$$

$$+ \sum_{i}\sum_{j}\sum_{m}^{M-1}\left\{\sum_{\underline{i}}\sum_{\underline{j}}\sum_{\underline{m}}^{M-1}(p_{m\underline{m}}h_{im}w_{\underline{i}m} + h_{iM}w_{\underline{i}M})(\sum_{\underline{n}}t_{n\underline{n}}x_{\underline{i}\underline{j}\underline{m}\underline{n}})\right\} x_{ijmn}$$

Combining the above terms:

$$t_n = \sum_i \sum_j a_{ijn}(b_{iMn} + s_{ijM} + e_{iM}) + \sum_i \sum_j \sum_{\underline{i}} \sum_{\underline{n}} \sum_{\underline{j}} h_{iM} w_{\underline{i}M} a_{\underline{i}\underline{j}\underline{n}} a_{ijn}$$

$$- \sum_i \sum_j \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} \sum_m^{M-1} g_{n\underline{n}} h_{iM} w_{\underline{i}M} a_{ijn} x_{\underline{i}\underline{j}m\underline{n}} + \sum_i \sum_j \sum_m^{M-1} (b_{imn} + s_{ijm} + e_{im} - b_{iMn} - s_{ijM} - e_{iM}) x_{ijmn}$$

$$- \sum_i \sum_j \sum_m^{M-1} \left\{ \sum_{\underline{i}} \sum_{\underline{j}} \left(h_{\underline{i}M} w_{iM} a_{\underline{i}\underline{j}n} + \sum_{\underline{n}} h_{iM} w_{\underline{i}M} a_{\underline{i}\underline{j}\underline{n}} \right) \right\} x_{ijmn}$$

$$+ \sum_i \sum_j \sum_m^{M-1} \left\{ \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{m}}^{M-1} (p_{m\underline{m}} h_{im} w_{\underline{i}m} + h_{iM} w_{\underline{i}M}) \left(\sum_{\underline{n}} t_{n\underline{n}} x_{\underline{i}\underline{j}\underline{m}\underline{n}} \right) \right\} x_{ijmn}$$

$$+ \sum_i \sum_j \sum_m^{M-1} \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{m}}^{M-1} \left\{ p_{m\underline{m}} h_{im} w_{\underline{i}m} + h_{iM} w_{\underline{i}M} \right\} x_{\underline{i}\underline{j}\underline{m}n} x_{ijmn}$$

$$g_{n\underline{n}} = \begin{cases} 0 \text{ if } n = \underline{n} \\ 1 \text{ if } n \neq \underline{n} \end{cases}$$

$$p_{m\underline{m}} = \begin{cases} 1 \text{ if } m = \underline{m} \\ 0 \text{ if } m \neq \underline{m} \end{cases}$$

$$t_{n\underline{n}} = \begin{cases} 0 \text{ if } n = \underline{n} \\ 1 \text{ if } n \neq \underline{n} \end{cases}$$

Considering the set of variables $\{x_{ijmn}\}$ for all i, j, m as a vector of dimension IJ(M-1), and by setting k = (i-1)(M-1)J + (m-1)J + j, we can rewrite the above equation in matrix form:

$$t_n = g - AX + \frac{1}{2}X'BX$$

$$g = \sum_i \sum_j \left\{ a_{ijn}(b_{iMn} + s_{ijM} + e_{iM}) + \sum_{\underline{i}} \sum_{\underline{j}} \sum_{\underline{n}} \{ h_{iM} w_{\underline{i}M} a_{\underline{i}\underline{j}\underline{n}} a_{ijn} - \sum_m^{M-1} g_{n\underline{n}} h_{iM} w_{\underline{i}M} a_{ijn} x_{\underline{i}\underline{j}m\underline{n}} \} \right\}$$

$$a_k = -b_{imn} - s_{ijm} - e_{im} + b_{iMn} + s_{ijM} + e_{iM} + \sum_{\underline{i}} \sum_{\underline{j}} \left\{ (h_{\underline{i}M} w_{iM} a_{\underline{i}\underline{j}n} + \sum_{\underline{n}} h_{iM} w_{\underline{i}M} a_{\underline{i}\underline{j}\underline{n}}) \right.$$

$$\left. - \sum_{\underline{m}}^{M-1} \{ (p_{m\underline{m}} h_{im} w_{\underline{i}m} + h_{iM} w_{\underline{i}\underline{m}})(\sum_{\underline{n}} t_{n\underline{n}} x_{\underline{i}\underline{j}\underline{m}\underline{n}}) \} \right\}$$

$$b_{k\underline{k}} = p_{m\underline{m}}(h_{im} w_{\underline{i}m} + h_{\underline{i}m} w_{im}) + h_{iM} w_{\underline{i}M} + h_{\underline{i}M} w_{iM}$$

PROOF OF POSITIVE SEMIDEFINITENESS

Statement of the Problem

The difficulty encountered in applying Dantzig's algorithm is that the quadratic matrix involved must be positive semidefinite. The cost structure of the multiple seaport model results in a problem of the following form:

Given a square, symmetric matrix B with $b_{k\underline{k}}$ such that:

$$b_{k\underline{k}} = d_{m\underline{m}}(h_{im}w_{\underline{i}m} + h_{\underline{i}\underline{m}}w_{i\underline{m}}) + h_{iM}w_{\underline{i}M} + h_{\underline{i}M}w_{iM}$$

$$k = (j-1)(M-1)NI + (n-1)(M-1)I + (m-1)I + i$$

$$\underline{k} = (\underline{j}-1)(M-1)NI + (\underline{n}-1)(M-1)I + (\underline{m}-1)I + i$$

$$d_{m\underline{m}} = \begin{cases} 1 \text{ if } m = \underline{m} \\ 0 \text{ if } m \neq \underline{m} \end{cases}$$

h_{im} = cost coefficient > 0
w_{im} = cost coefficient > 0

I = number of commodities in system
J = number of destinations in system
M = number of ports in system
N = number of sources in system

$1 \leq i \leq I$ $\quad$ $1 \leq \underline{i} \leq I$

$1 \leq j \leq J$ $\quad$ $1 \leq \underline{j} \leq J$

$1 \leq m \leq M-1$ $\quad$ $1 \leq \underline{m} \leq M-1$

$1 \leq n \leq N$ $\quad$ $1 \leq \underline{n} \leq N$

(the equation defining k gives a one-to-one correspondence between values of k and sets of ijmn; the same holds true for $\underline{k}$)

Prove: B is positive semidefinite.

Solution

From the given conditions, we see that

$$b_{k\underline{k}} = d_{m\underline{m}}(h_{im}w_{\underline{i}m} + h_{\underline{im}}w_{i\underline{m}})$$

$$+ h_{iM}w_{\underline{i}M} + h_{\underline{i}M}w_{iM}$$

$$h_{im} > 0 \text{ for all } i,m$$

$$w_{im} > 0 \text{ for all } i,m$$

$$d_{m\underline{m}} \geq 0 \text{ for all } m,\underline{m}$$

This clearly implies that:

$$b_{k\underline{k}} > 0 \text{ for all } k,\underline{k}$$

Now, consider two columns in the matrix B, namely, columns $\underline{k}'$ and $\underline{k}''$

$$\bar{b}_{k\underline{k}'} = \begin{bmatrix} b_{1\underline{k}'} \\ b_{2\underline{k}'} \\ b_{3\underline{k}'} \\ \vdots \\ b_{k\underline{k}'} \end{bmatrix} \qquad \bar{b}_{k\underline{k}''} = \begin{bmatrix} b_{1\underline{k}''} \\ b_{2\underline{k}''} \\ b_{3\underline{k}''} \\ \vdots \\ b_{k\underline{k}''} \end{bmatrix}$$

If we look at the $\underline{\underline{k}}$ element of both columns, we see that they are defined by:

$$b_{\underline{\underline{k}}\underline{k}'} = d_{\underline{\underline{m}}\underline{m}'}(h_{\underline{\underline{i}}\underline{\underline{m}}}w_{\underline{i}'\underline{\underline{m}}} + h_{\underline{i}'\underline{m}'}w_{\underline{\underline{i}}\underline{m}'} + h_{\underline{\underline{i}}M}w_{\underline{i}'M} + h_{\underline{i}'M}\,w_{\underline{\underline{i}}M}$$

$$b_{\underline{\underline{k}}\underline{k}''} = d_{\underline{\underline{m}}\underline{m}''}(h_{\underline{\underline{i}}\underline{\underline{m}}}w_{\underline{i}''\underline{\underline{m}}} + h_{\underline{i}''\underline{m}''}w_{\underline{\underline{i}}\underline{m}''}) + h_{\underline{\underline{i}}M}w_{\underline{i}''M} + h_{\underline{i}''M}\,w_{\underline{\underline{i}}M}$$

Inspection shows that if:

$$\underline{m}' = \underline{m}'' \quad \text{and} \quad \underline{i}' = \underline{i}''$$

then:

$$b_{\underline{\underline{k}}\underline{k}'} = b_{\underline{\underline{k}}\underline{k}''}$$

Since this is true for all $\underline{\underline{k}}$, it follows that:

$$\bar{b}_{\underline{\underline{k}}\underline{k}'} = \bar{b}_{\underline{\underline{k}}\underline{k}''}$$

In short, that columns k' and k" are identical.

The conditions for this to be true are that:

$$\underline{m}' = \underline{m}'' \quad \text{and} \quad \underline{i}' = \underline{i}''$$

To show that two columns, $\underline{k}'$ and $\underline{k}''$, exist such that:

$$\underline{k}' \neq \underline{k}''$$

and such that the above two conditions are satisfied, we begin with their definitions:

$$\underline{k}' = (\underline{j}'-1)(M-1)NI + (\underline{n}'-1)(M-1)I + (\underline{m}'-1)I + \underline{i}'$$

$$k'' = (\underline{j}''-1)(M-1)NI + (\underline{n}''-1)(M-1)I + (\underline{m}''-1)I + \underline{i}''$$

Setting $\underline{m}'=\underline{m}''$ and $\underline{i}'=\underline{i}''$, we get:

$$\underline{k}' = (\underline{j}'-1)(M-1)NI + (n'-1)(M-1)I + C$$

$$\underline{k}'' = (\underline{j}''-1)(M-1)NI + (n''-1)(M-1)I + C$$

$$C = (\underline{m}'-1)I + \underline{i}' = \text{constant}$$

We wish:

$$\underline{k}' \neq \underline{k}''$$

This implies that:

$$(\underline{j}'-1)N + (\underline{n}'-1) \neq (\underline{j}''-1)N + (\underline{n}''-2)$$

Recalling that:

$$1 \leq j' \leq J$$
$$1 \leq j'' \leq J$$
$$1 \leq n' \leq N$$
$$1 \leq n'' \leq N$$

It is clear that if either N > 1 or J > 1, at least one set of $\underline{j}'$, $\underline{j}''$, $\underline{n}'$ and $\underline{n}''$ can be found which satisfies this condition. For instance, if $\underline{j}' = \underline{j}''+1$, the condition is satisfied.

Thus, if either N > 1 or J > 1, at least two columns in matrix B are identical. With proper relabeling of variables, these columns can be made to be the two left-most columns.

A necessary and sufficient condition[1] for a square, symmetric matrix to be positive semidefinite is that all its principal minors are greater than or equal to zero. That is, given:

$$B = \begin{bmatrix} b_{11} & b_{12} & b_{13} \cdots & b_{1k} \\ b_{21} & b_{22} & b_{23} \cdots & b_{2k} \\ b_{31} & b_{32} & b_{33} \cdots & b_{3k} \\ \vdots & \vdots & \vdots & \vdots \\ b_{k1} & b_{k2} & b_{k3} & b_{kk} \end{bmatrix}$$

if:

$$\det [\, b_{11}] \geq 0$$

[1] Matrix Theory, Gant-Macher, Chelsea Publishing Company, 1970, p. 307.

$$\det \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \geq 0$$

$$\det \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \geq 0$$

$$\vdots$$

$$\det B \geq 0$$

Then B is positive semidefinite.

It has been shown that $b_{k\underline{k}} > 0$ for all k, $\underline{k}$. Thus:

$$\det (b_{11}) = b_{11} > 0$$

It has been shown that the first two columns of B are identical, and thus, that the first two columns of all its minors are identical. Since the determinate of any matrix with two identical columns is zero, we see that the equality holds for all succeeding minors. Thus, B satisfies the conditions and is positive semidefinite.

Discussion

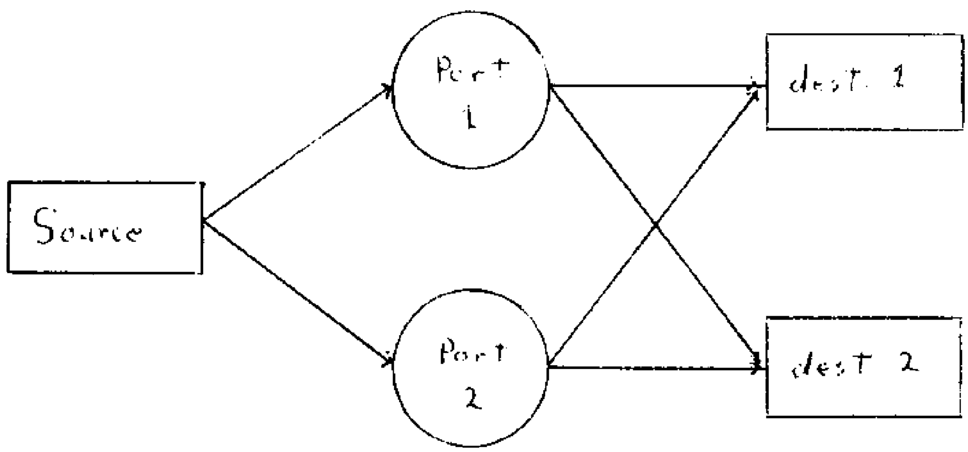
The preceding proof is valid for the matrix formulation involved when the objective function to be minimized is the sum of the costs incurred by all the sources. For the formulation in which only those costs incurred by a single source are considered, an analogous proof exists. The only difference in results is that the condition for convexity is that $J > 1$, rather than either $J > 1$ or $N > 1$. For simplicity, we can simply insist that J, the number of overseas destinations in the system, be greater than one.

The condition that the cost coefficients are positive is satisfied by all reasonable systems. A negative coefficient would imply that as a port became congested, shipping costs would decrease. It is very doubtful that this would be the case.

SAMPLE PROBLEM

Introduction

For explanatory purposes, this appendix presents a seaport transportation network and its solution through the use of Dantzig's Simplex algorithm. The example model contains two ports, one inland source, two types of cargo, and two overseas destinations.



Model Parameters

$I = 2$

$J = 2$

$M = 2$

$N = 1$

b_{imn}:	$b_{111} = 3$ \$/unit	$b_{211} = 4$
	$b_{121} = 4$	$b_{221} = 5$
s_{ijm}:	$s_{111} = 3$ \$/unit	$s_{211} = 4$
	$s_{112} = 7$	$s_{212} = 8$
	$s_{121} = 8$	$s_{221} = 5$
	$s_{122} = 4$	$s_{222} = 3$

e_{im}: $e_{11} = 2$ \$/unit $e_{21} = 3$

$e_{12} = 5$ $e_{22} = 6$

w_{im}: $w_{11} = 0.5$ units congestion/flow $w_{21} = 0.5$

$w_{12} = 0.25$ $w_{22} = 0.2$

h_{im}: $h_{11} = 1.0$ \$/unit congestion $h_{21} = 1.0$

$h_{12} = 0.75$ $h_{22} = 0.8$

a_{ijn}: $a_{111} = 15$ units $a_{211} = 3$

$a_{121} = 5$ $a_{221} = 7$

Constraints:

$$X_1 + X_2 \leq 10$$

$$S_3 + 2X_4 \leq 15$$

Index Table:

k	i	j	m	n
1	1	1	1	1
2	1	2	1	1
3	2	1	1	1
4	2	2	1	1

The above data yield matrices with the following values:

$$B = \begin{bmatrix} 1.375 & 1.375 & 1.35 & 1.35 \\ 1.375 & 1.375 & 1.35 & 1.35 \\ 1.35 & 1.35 & 1.32 & 1.32 \\ 1.35 & 1.35 & 1.32 & 1.32 \end{bmatrix}$$

$$A^* = \begin{bmatrix} 19 \\ 11 \\ 18.2 \\ 12.2 \end{bmatrix}$$

$$C^{*'} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 2 \end{bmatrix}$$

$$d = \begin{bmatrix} 15 \\ 5 \\ 3 \\ 7 \\ 10 \\ 15 \end{bmatrix}$$

Noting that $d > 0$, we can immediately write a basic feasible standard form:

BV	VBV	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9	Z_{10}	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}
U_1	-19	-1.375	-1.375	-1.35	-1.35	0	0	0	0	0	0	1	0	0	0	-1	0	0	0	-1	0
U_2	-11	-1.375	-1.375	-1.35	-1.35	0	0	0	0	0	0	0	1	0	0	0	-1	0	0	-1	0
U_3	-18.2	-1.35	-1.35	-1.32	-1.32	0	0	0	0	0	0	0	0	1	0	0	0	-1	0	0	-1
U_4	-12.2	-1.35	-1.35	-1.32	-1.32	0	0	0	0	0	0	0	0	0	1	0	0	0	-1	0	-2
Z_5	15	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z_6	5	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z_7	3	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Z_8	7	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Z_9	10	1*	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Z_{10}	15	0	0	1	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

BV	VBV	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9	Z_{10}	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}
U_1	-5.25	0	0	-1.35	-1.35	0	0	0	0	1.375	0	1	0	0	0	-1	0	0	0	-1*	0
U_2	2.75	0	0	-1.35	-1.35	0	0	0	0	1.375	0	0	1	0	0	0	-1	0	0	-1	0
U_3	-4.7	0	0	-1.32	-1.32	0	0	0	0	1.35	0	0	0	1	0	0	0	-1	0	0	-1
U_4	1.3	0	0	-1.32	-1.32	0	0	0	0	1.35	0	0	0	0	1	0	0	0	-1	0	-2
Z_5	5	0	-1	0	0	1	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0
Z_6	5	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z_7	3	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Z_8	7	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Z_1	10	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Z_{10}	15	0	0	1	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

BV	VBV	z_1	z_2	z_3	z_4	z_5	z_6	z_7	z_8	z_9	z_{10}	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}
U_9	5.25	0	0	1.35	1.35	0	0	0	0	-1.375	0	-1	0	0	0	1	0	0	0	1	0
U_2	8.0	0	0	0	0	0	0	0	0	0	0	-1	1	0	0	1	-1	0	0	0	0
U_3	-4.7	0	0	-1.32	-1.32	0	0	0	0	1.35	0	0	0	1	0	0	0	-1	0	0	-1
U_4	1.3	0	0	-1.32	-1.32	0	0	0	0	1.35	0	0	0	0	1	0	0	0	-1	0	-2
z_5	5	0	-1	0	0	1	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0
z_6	5	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
z_7	3	0	0	1*	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
z_8	7	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
z_1	10	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
z_{10}	15	0	0	1	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

BV	VBV	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9	Z_{10}	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}
U_9	1.20	0	0	0	1.35	0	0	-1.35	0	-1.375	0	-1	0	0	0	1	0	0	0	1	0
U_2	8	0	0	0	0	0	0	0	0	0	0	-1	1	0	0	1	-1	0	0	0	0
U_3	-.74	0	0	0	-1.32	0	0	1.32	0	1.35	0	0	0	1	0	0	0	-1*	0	0	-1
U_4	5.26	0	0	0	-1.32	0	0	1.32	0	1.35	0	0	0	0	1	0	0	0	-1	0	-2
Z_5	5	0	-1	0	0	1	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0
Z_6	5	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z_3	3	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Z_8	7	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Z_1	10	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Z_{10}	15	0	0	1	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

BV	VBV	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9	Z_{10}	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}
U_9	1.2	0	0	0	1.35	0	0	-1.35	0	-1.375	0	-1	0	0	0	1	0	0	0	1	0
U_2	8	0	0	0	0	0	0	0	0	0	0	-1	1	0	0	1	-1	0	0	0	0
U_7	.74	0	0	0	1.32	0	0	-1.32	0	-1.35	0	0	0	-1	0	0	0	1	0	0	1
U_4	5.26	0	0	0	-1.32	0	0	1.32	0	1.35	0	0	0	0	1	0	0	0	-1	0	-2
Z_5	5	0	-1	0	0	1	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0
Z_6	5	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Z_3	3	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Z_8	7	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Z_1	10	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Z_{10}	15	0	0	1	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

The final iteration leaves us with the X-vector:

$$X_1 = 10$$

$$X_2 = 0$$

$$X_3 = 3$$

$$X_4 = 0$$

Using this information and the equality constraints of the form:

$$X_{ijMn} = a_{ijn} - \sum_{m}^{M-1} X_{ijmn}$$

we can find all the cargo flows:

$$X_{1111} = 10 \qquad X_{2111} = 3$$

$$X_{1121} = 5 \qquad X_{2121} = 0$$

$$X_{1211} = 0 \qquad X_{2211} = 0$$

$$X_{1221} = 5 \qquad X_{2221} = 7$$

APPENDIX B

AN APPRAISAL OF QUEUING MODELS
FOR THE SOLUTION
OF PORT CAPACITY PROBLEMS

by

Antonio G. N. Novaes

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AN APPRAISAL OF QUEUING MODELS FOR THE SOLUTION OF PORT CAPACITY PROBLEMS

Antonio G. N. Novaes

Introduction

Until recently queuing models were developed in a very strict mathematical sense, leading to exact solutions when the problem could be solved analytically but remaining unsolved otherwise.

The literature abounds with a huge number of papers in queuing theory, a situation that has some resemblance to the "theme and variations" scheme encountered in classical music.

Applied operations researchers are interested in solving real problems and therefore simulation models have often been used whenever the mathematical models are not available. Simulation, however, is a poor tool since it does not improve the knowledge of the basic problem as much as the analytic models usually do.

Lately applied operations researchers can feel more hope for queuing theory applications, due to recent developments in the area of queue bound analysis.

Prof. Ronald Wolff of the University of California at Berkeley and his group have been making research in this field during the last few years, with promising results.

In this report we intend to analyze the state of the art in Queuing Theory as far as port development problems are concerned.

2. Basic Queuing Models

In this section we will analyze some basic facts related to the classical queuing models that usually appear in the O.R. text books.

2.1 Queue Classification

Queues are classified usually according to Kendall's scheme which, in general, is the following:

X/Y/C

- C — number of channels or service stations
- Y — symbol for the service time distribution
- X — symbol for the interarrival time distribution

The queue with Poisson arrivals and exponential service time, with C service stations, is referred to as the M/M/C queue (perhaps the M stands for Markovian). The queue with service time distributed according to a k^{th} order Erlangian distribution, Poisson arrivals and C service stations, is called $M/E_k/C$.

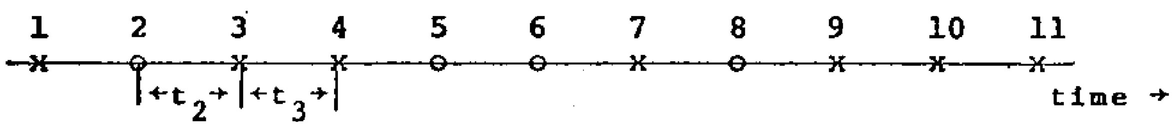
The queue with deterministic input and constant service times is referred to as the D/D/C queue.

Finally, the GI/G/C symbol represents a queue in which the interarrival times are independently distributed according to a general A(t) distribution, and the service time is described by a general G(t) distribution.

2.2 Birth-and-Death Queues

Poisson queues are those with Poisson arrival and exponential service times. Most Poisson queues are, in general, easy to handle analytically due to some special properties of the Poisson process.

To understand this better let us consider an M/M/1 queue. This queue is analyzed at discrete epochs, namely, the instants in which occur an arrival or a departure. Those epochs are called "events" and can succeed in a very random sequence:



o - departures
x - arrivals

Figure 1

If we take events 3 and 4 (both arrivals) we know that they are independent events, since the arrival process is Poisson. On the other hand, if we take events 2 and 3 - a departure followed by an arrival - one is not sure at first glance if they are really independent events.

Looking at Figure 1 one would guess that as time elapses starting from event 1, the chances of getting a new arrival increases. This is not true, in fact, with the Poisson process. The Poisson process has the property of "forgetting" the past, i.e., the time distribution to next arrival is the same for any instant t, regardless of the fact of whether t corresponds to an arrival or not (see Morse [7]).

This property allows us to analyze Poisson queues through a Markovian approach. Most of them, in fact, can be classified within a particular class of Markov processes, namely, the "birth-and-death" process, for which exact solutions are known.

A birth-and-death process is a continuous-time Markov process in which the differential matrix $\underline{A}$ is a "band matrix"*, formed only by the diagonal and the two adjacent bands:

$$\underline{A} = \begin{bmatrix} c_o & d_o & 0 & 0 & \cdot & \cdot & \cdot & \cdot & \cdot \\ b_1 & c_1 & d_1 & 0 & 0 & \cdot & \cdot & \cdot & \cdot \\ 0 & b_2 & c_2 & d_2 & 0 & 0 & \cdot & \cdot & \cdot \\ 0 & 0 & b_3 & c_3 & d_3 & 0 & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & b_n & c_n & d_n \end{bmatrix} \qquad (1)$$

The Chapman-Kolmogorov forward equation for a continuous-time Markov process can be written in matrix form as follows:

$$\frac{\partial \underline{\pi}(t)}{\partial t} = \underline{\pi}(t) \cdot \underline{A} \qquad (2)$$

where $\underline{\pi}(t)$ is the state occupancy vector at time t. If the process is ergodic, then $\lim_{t\to\infty} \pi(t) = \pi$ and therefore $\lim_{t\to\infty} \frac{\partial \underline{\pi}(t)}{\partial t} = 0$, yielding:

$$\underline{\pi} \cdot \underline{A} = \underline{0} \qquad (3)$$

Applying equation (3), one can get the state occupancy probabilities π_o, π_1, ... which are given by

*We borrow this term from matrix structural analysis.

$$\pi_n = \pi_o \prod_{i=1}^{n} \frac{d_{i-1}}{b_i} \qquad (4)$$

since $\sum_j a_{ij} = 0$ for any i, and therefore $c_i = -(b_i + d_i)$ for $i = 0, 1, 2, \ldots$

Equation (4) plus $\sum_{i=0}^{\infty} \pi_i = 1$ yield the steady-state probabilities $\pi_o, \pi_1, \pi_2, \ldots$ (5)

Thus, for any Poisson queue that can be described by a birth-and-death process, one is only required to define matrix $\underline{A}$ and from there just apply expressions (4) and (5).

Of particular importance, among birth-and-death process queues, is the M/M/C queue. Saaty [12] presents both the transient and the steady state solution for such a queue (Chapter 4, Section 4-F).

The results for the M/M/C queue can be summarized as follows:

$$\pi_i = \frac{\pi_o}{i!} \left(\frac{\lambda}{\mu}\right)^i \quad \text{for} \quad 1 \leq i \leq c \qquad (6)$$

$$\pi_i = \frac{\pi_o}{c!} \left(\frac{\lambda}{c\mu}\right)^i c^c \quad \text{for} \quad i > c \qquad (6)$$

$$\pi_o = \frac{1}{\sum_{i=0}^{c-1} \frac{(c\rho)^i}{i!} + \frac{(c\rho)^c}{c!(1-\rho)}} \qquad (7)$$

$$\text{where} \quad \rho = \frac{\lambda}{c\mu} = \text{traffic intensity} \qquad (8)$$

The average number in the queue L_q is given by:

$$\bar{L}_q = \frac{\rho(c\rho)^c}{c!(1-\rho)^2} \pi_o \qquad (9)$$

from which one can compute the average waiting time in the queue by using the relation:

$$\bar{W}_q = \frac{L_q}{\lambda} = \frac{(c\rho)^c \pi_o}{c!(1 - \rho)} \quad \frac{1}{\mu c(1 - \rho)} \tag{10}$$

Finally, the cumulative waiting time distribution in the queue (not including service time) is given by:

$$P(\leq w) = 1 - P(>0) \exp[- \frac{\lambda}{\rho} (1 - \rho)w] \tag{11}$$

where $P(>0)$ is the probability that an arrival must wait, which can be expressed as:

$$P(>0) = \frac{(c\rho)^c}{c!(1 - \rho)} \pi_o \tag{12}$$

2.3 An Example

The above model was applied to analyze congestion at the port of Santos, Brazil (Novaes [9]). The analysis dealt with general cargo ship terminals only, excluding coastwise trade, which is handled in a separate terminal.

A sample of ships, covering the whole year of 1968, was analyzed, leading to the results shown in Table I and Figure 1. Statistical tests indicated that a Poisson distribution fits the data quite well.

Next, the service time distribution was analyzed. For this we had to separate the analysis into two steps. The first step was to study the tonnage loaded/unloaded per ship. Table II shows the tonnage distribution per vessel. The cumulative distribution is displayed in Figure 2, together with the exponential cumulative distribution. One can see that they agree quite well.

Table I

SAMPLE OF SHIP ARRIVALS (1968)

Port of Santos, Brazil (*)

Arrivals (Ships/Day)	No. of Cases	Actual Relative Frequency	Poisson Relative Frequency
0	11	0.030	0.030
1	37	0.101	0.104
2	69	0.189	0.183
3	78	0.214	0.215
4	68	0.186	0.189
5	56	0.154	0.133
6	21	0.057	0.078
7	15	0.041	0.039
8	3	0.008	0.017
9	3	0.008	0.007
10	2	0.006	0.002
11	1	0.003	0.001
12	1	0.003	0.000
>12	0	0.000	0.000
	365	1.000	0.998

*The ships included in the sample belong to the Interamerican Freight Conference.

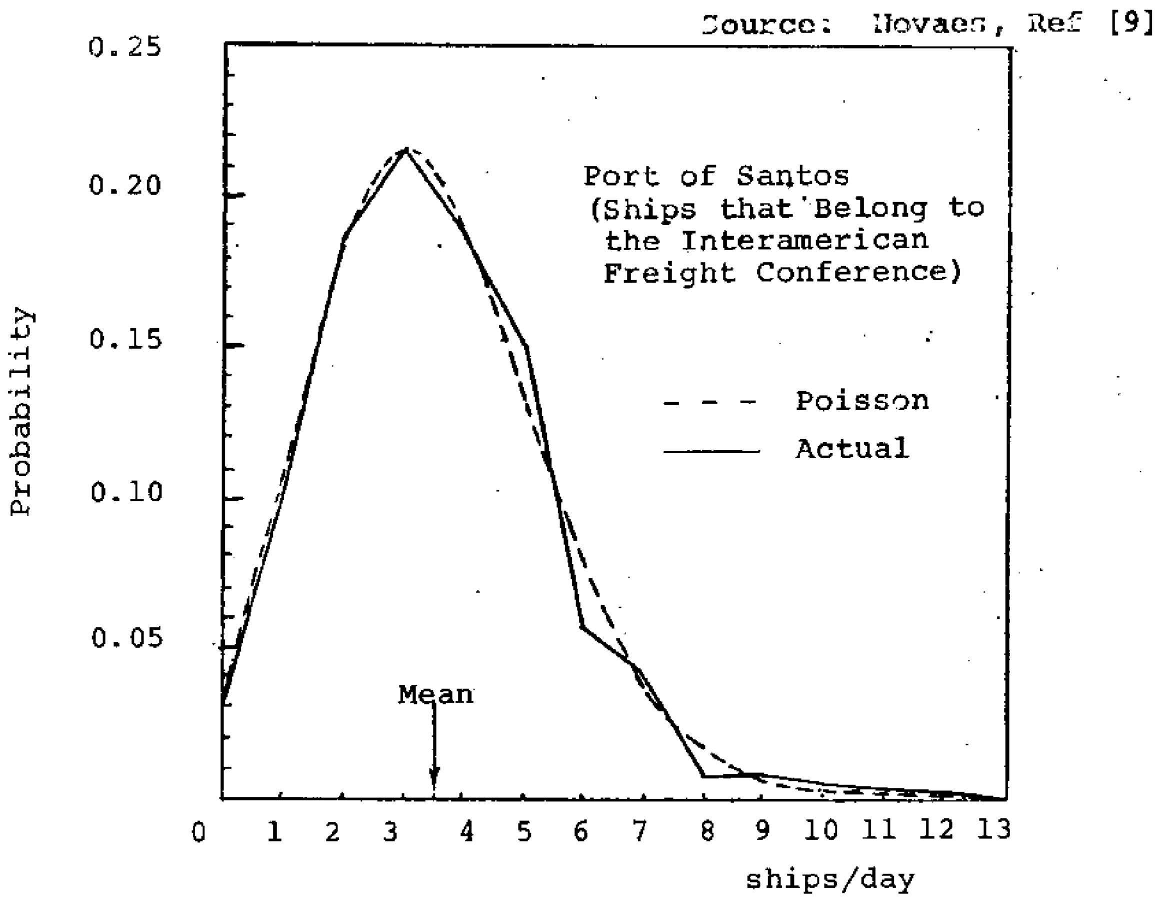


Figure 1

Ship Arrival Distribution

Table II

DISTRIBUTION OF CARGO (LOADED/UNLOADED) PER SHIP

(1968)

Amount of Cargo per Ship (tons)	No. of Cases	Cumulative Frequency	Cumulative Exponential Distribution
0 - 500	472	0.364	0.336
500 - 1,000	261	0.566	0.560
1,000 - 1,500	194	0.716	0.708
1,500 - 2,000	115	0.805	0.806
2,000 - 2,500	95	0.878	0.871
2,500 - 3,000	49	0.916	0.915
3,000 - 3,500	41	0.948	0.943
3,500 - 4,000	17	0.962	0.962
4,000 - 4,500	17	0.975	0.975
4,500 - 5,000	14	0.985	0.985
5,000 - 6,000	3	0.987	0.988
6,000 - 7,000	6	0.992	0.997
7,000 - 10,000	5	0.994	1.000
> 10,000	5	1.000	1.000
	1294		

Average: 1220 tons/ship

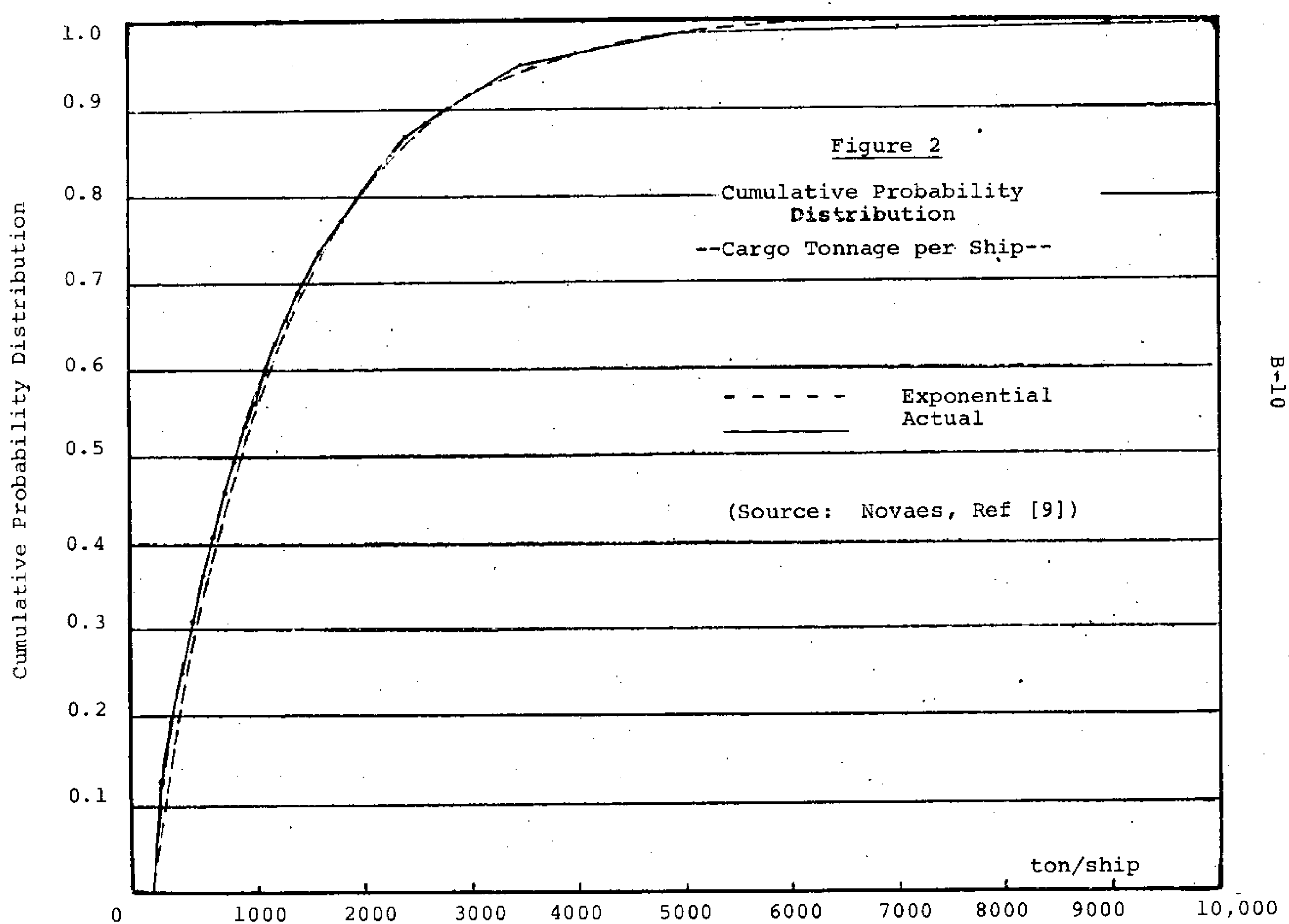


Figure 2
Cumulative Probability Distribution
--Cargo Tonnage per Ship--
Exponential
Actual
(Source: Novaes, Ref [9])
Cumulative Probability Distribution
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10,000
ton/ship

The second step is to determine the time necessary to load/unload the ship. Figure 3 shows the curve fitted to the data, leading to an average of 425 tons/day. In fact, the actual tonnages handled for each bracket (one day stay, 2 days, 3 days, etc.) showed a relatively high dispersion, meaning that the resulting service time (combination of both distributions) is really hyper-exponential (see Section 3). This will lead to a somewhat distorted result, as we will see later.

For the ships with which we are dealing, the Port of Santos had about 25 berths. The average number of vessels that arrived in Santos in 1968 was 8.25 ships/day, only considering general cargo vessels and excluding coastal ships.

The observed delays incurred by those ships in 1968 are shown in Table III.

We applied the M/M/C queue model, with $\lambda = 8.25$ arrivals/day, $1/\mu = 1220/425 = 2.87$ days/ship, and $c = 25$, leading to $\rho = 0.945$. The year of 1968 was one of the worst years in the history of the Port of Santos, as far as congestion is concerned. Since then, other facilities have been added, with the result that today the traffic intensity coefficient (ρ) is lower.

Figure 4 displays the cumulative waiting time distributions (exponential) for various values of ρ. These curves are given by equation (11). Figure 4 also shows the cumulative distribution of the real delays. We see that, although the observed curve follows the theoretical curve for $\rho = 0.945$, it nevertheless displays a distortion. For small values of w the

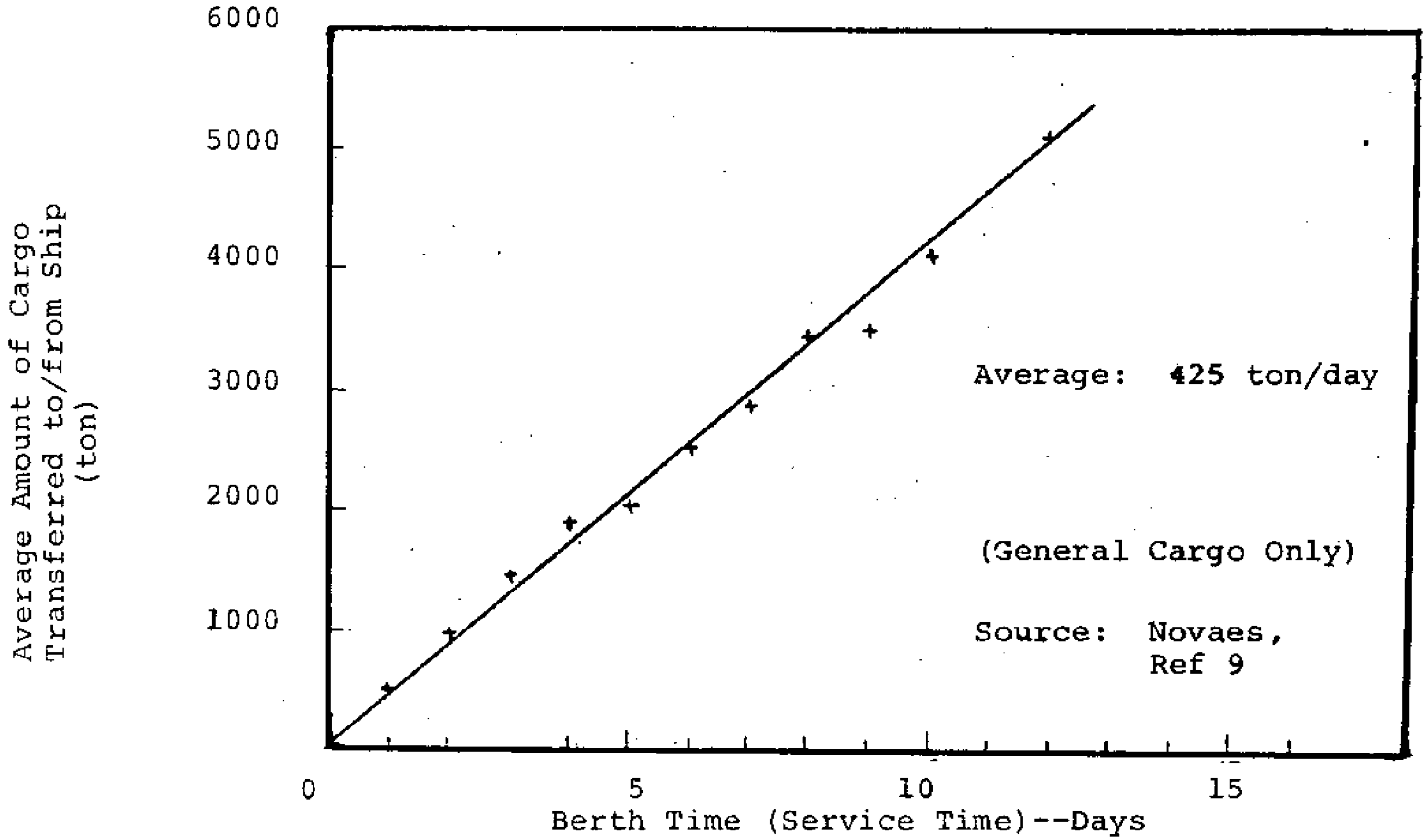
Table III

OBSERVED SHIP DELAYS

(WAITING TIME BEFORE MOORING)

Santos (1968)

Delay (days)	No. of Cases
0	1695
1	524
2	253
3	160
4	108
5	64
6	56
7	34
8	29
9	30
10	17
11	8
12	7
13	7
14	2
15	2
16	7
17	4
18	0
19	2
20	0
21	1
Total No. of Cases	3010



<u>Figure 3</u>

Amount of Cargo Transferred × Time Spent at Berth

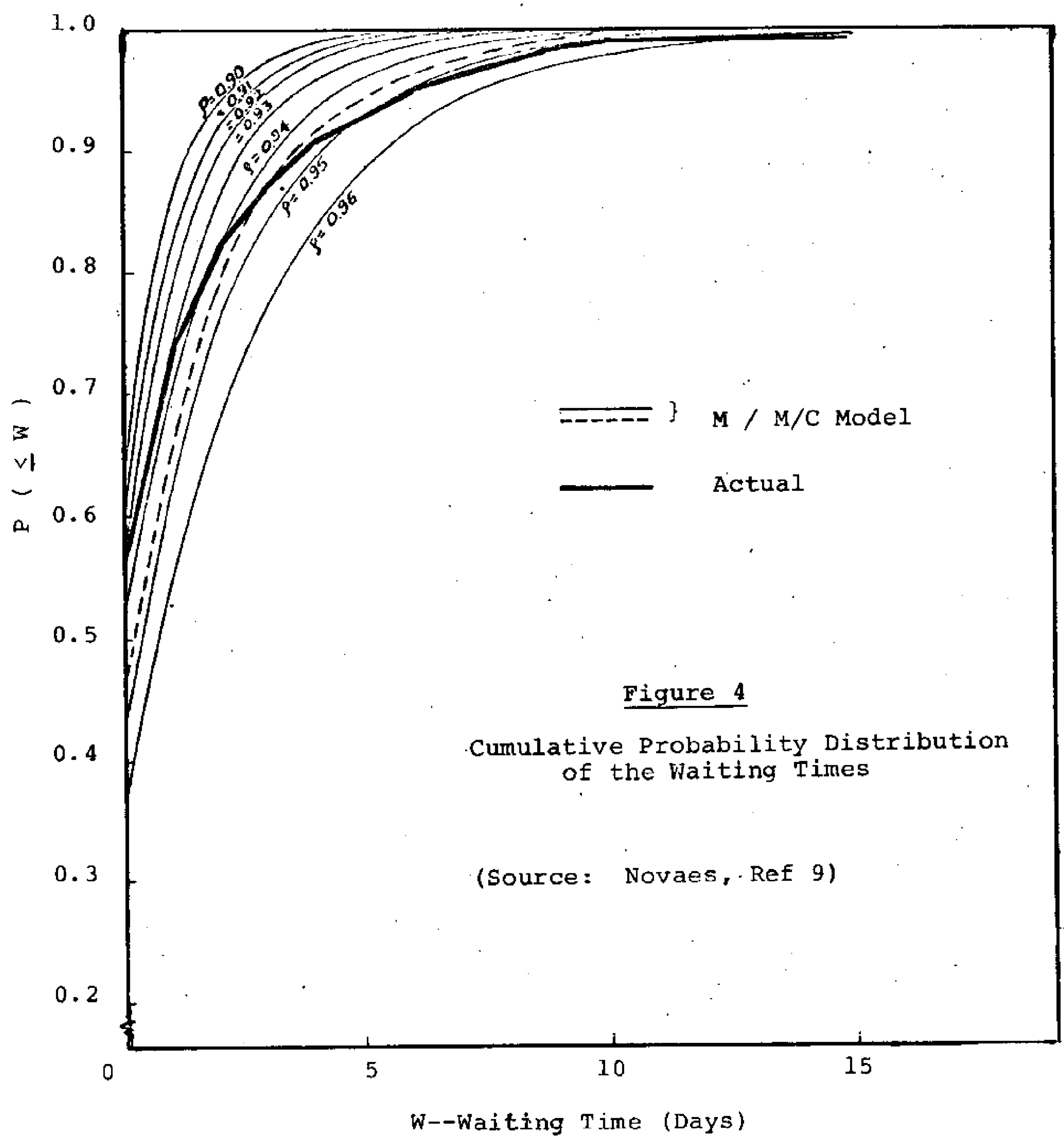


Figure 4

Cumulative Probability Distribution of the Waiting Times

(Source: Novaes, Ref 9)

real figures are higher than the corresponding theoretical ones; for larger values of w the opposite is true. This is due to the assumption of exponential service times, when in reality they are distributed according to a hyper-exponential distribution.

The expected delay, computed through the queuing model, was 1.13 days/ship; the real average waiting time was 1.35 days/ship, or 19% greater, the difference being caused perhaps by the approximation in service time distribution.

3. The $M/E_k/C$ Queue

3.1 Erlang and Hyper-Exponential Distributions

An Erlang distribution of order k can be seen as the sum of k independent and identical exponential distributions. Let b(t) be an exponential distribution of t, whose probability density function is given by:

$$b(t) = \mu e^{-\mu t} \tag{13}$$

The mean and the variance are given by:

$$E(t) = \frac{1}{\mu} \tag{14}$$

and

$$\sigma_t^2 = \frac{1}{\mu^2} \tag{15}$$

Therefore the mean and variance of a k-Erlang distribution can be easily computed by adding k equal terms:

$$\bar{T} = E[T] = \frac{k}{\mu} \tag{16}$$

and

$$\sigma_T^2 = \frac{k}{\mu^2} \tag{17}$$

where T is the Erlang-distributed time. Thus, if one has obtained through the data the average and the variance, the parameters of the Erlang distribution (if applicable) can be computed through (16) and (17), leading to:

$$k = \overline{T}^2/\sigma_T^2 \tag{18}$$

and

$$\mu = \overline{T}/\sigma_T^2 \tag{19}$$

The Erlang probability density function of T is, for k integer:

$$f(T) = \frac{\mu^k}{(k-1)!} T^{k-1} e^{-\mu T} \qquad T \geq 0 \tag{20}$$

The Laplace transform of f(T) can be shown to be:

$$F^T(s) = \left(\frac{\mu}{\mu + s}\right)^k \tag{21}$$

Some interesting properties are associated with the Erlang distribution:

(a) For $k = 1$, we have obviously an exponential distribution.

(b) For $k > 1$, it can be shown that the coefficient of variation of T decreases, i.e., the dispersion diminishes. In fact, from (16) and (17) we get:

$$C_v(T) = \frac{\sigma_T}{\overline{T}} = \frac{1}{\sqrt{k}} \tag{22}$$

Thus, for $k = 1$ one has $C_v(T) = 1$, but for $k = 25$, $C_v(T) = 0.20$.

(c) As k increases, the Erlang distribution tends towards a normal distribution (central limit theorem).

(d) If we make $k \to \infty$, keeping k/μ = constant, we have from (16) $k/\mu = \bar{T}$, from which we take $\mu = k/\bar{T}$. Putting in (21) and getting the limit, we have:

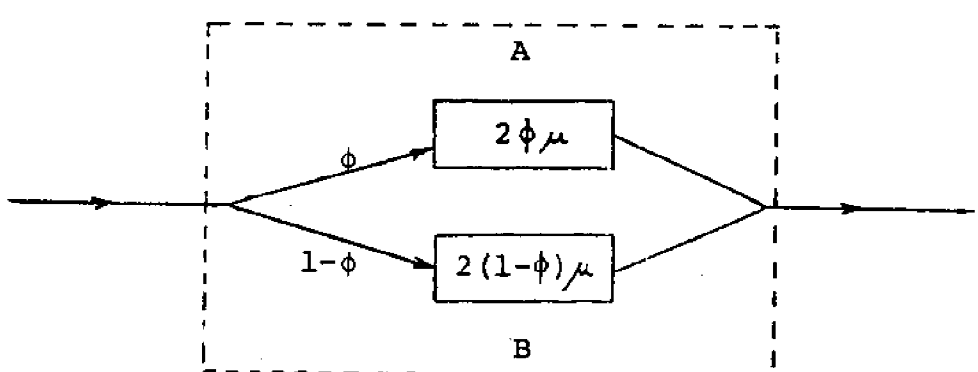
$$\lim_{k\to\infty} F^T(s) = \lim_{k\to\infty} \left(\frac{k}{k + s\bar{T}}\right)^k = \lim_{k\to\infty} \left(1 + \frac{s\bar{T}}{k}\right)^{-k} = e^{-s\bar{T}} \qquad (23)$$

But this is the lagged Laplace transform of a unit impulse (which occurs at $\bar{T}$), which means that it represents the deterministic case, namely:

$$\begin{aligned} &P(\bar{T}) = 1 \qquad \text{for } T = \bar{T} \\ \text{and} \quad &P(\bar{T}) = 0 \qquad \text{otherwise} \end{aligned} \qquad (24)$$

This latter case has a coefficient of variation equal to zero. Thus the Erlang family of distributions covers a range of C_v from 1.0 to zero as $k \to \infty$.

Some distributions, however, present $C_v > 1$ as, for instance, the hyper-exponential distribution. The hyper-exponential distribution is not an Erlang distribution, but can be derived from a combination of two exponential distributions in parallel. For this one considers two channels operating alternatively, i.e., they cannot operate at the same time. Let ϕ be the probability that a customer chooses channel A, and $1 - \phi$ be the probability of choosing channel B.



Furthermore, let us assume that both channels have service time distributed according to exponential distributions such that:

$$\mu_A = 2\phi\mu \tag{25}$$

and
$$\mu_B = 2(1 - \phi)\mu \tag{26}$$

Morse [7] shows that the variance of the service time is given by

$$\sigma_T^2 = \frac{1}{\mu^2}\left[1 + \frac{(1 - 2\phi)^2}{2\phi(1 - \phi)} \right] = \frac{a}{\mu^2} \tag{27}$$

Then, from (27) one writes:

$$C_v(T) = \frac{\sigma_T}{\bar{T}} = \mu\sigma_T = \sqrt{a} \qquad 0 < \phi \leq 1/2 \tag{28}$$

For $\phi = 1/2$, a = 1 and we have the exponential case. For $\phi \to 0$, a > 1 and therefore $C_v(T) > 1$, leading to the hyper-exponential configuration.

3.2 The $M/E_\infty/C$ Queue

This type of queue was first studied by Crommelin, back in 1932/1934. Saaty [12] presents a good description of Crommelin's work (Section 6-2, Chapter 6).

The main results obtained by Crommelin, as presented by Saaty, are the following:

$$\bar{W}_q = P(>0) \cdot \frac{1}{\mu c(1 - \rho)} \cdot \frac{c}{c + 1} \cdot \frac{1 - \rho^{c+1}}{1 - \rho^c} \tag{29}$$

$$P(>0) = \frac{\dfrac{\rho c\, e^{-\rho c}}{c!(1 - \rho)}}{1 - e^{-\rho c}\displaystyle\sum_{i=c}^{\infty}\frac{(\rho c)^i}{i!} + \dfrac{\rho c^c e^{-\rho c}}{c!(1 - \rho)}} \tag{30}$$

This last expression can be easily simplified, remembering that $\sum_{i=0}^{\infty} \frac{(\rho c)^2}{i!} = e^{\rho c}$, leading to:

$$P(>0) = \frac{\frac{(c\rho)^c}{c!(1-\rho)}}{\sum_{i=0}^{c-1} \frac{(c\rho)^i}{i!} + \frac{(c\rho)^c}{c!(1-\rho)}} \tag{31}$$

which is exactly P(>0) as given by (12).

Let us call $W_q^{(1)}$ the expected waiting time in queue M/M/C, and $\bar{W}_q^{(\infty)}$ the expected waiting time in queue $M/E_\infty/C$. The first is given by (10) and the latter by relation (29). The ratio is:

$$\frac{\bar{W}_q^{(1)}}{\bar{W}_q^{(\infty)}} = \frac{c+1}{c} \cdot \frac{1-\rho^c}{1-\rho^{c+1}}$$

$$\text{with} \quad \lim_{c\to\infty} \frac{\bar{W}_q^{(1)}}{W_q^{(\infty)}} = 1 \tag{33}$$

In fact, the ratio converges quite fast toward the limit: for c = 25 and ρ = 0.945, as in the example of Section 2.3, we get $\bar{W}_q^{(1)}/\bar{W}_q^{(\infty)} = 1.02$.

The queue $M/E_k/C$, with k finite (k>1), presents an expected waiting time located between $\bar{W}_q^{(1)}$ and $\bar{W}_q^{(\infty)}$, i.e.,

$$W_q^{(\infty)} < W_q^{(k)} < W_q^{(1)} \tag{34}$$

Therefore, as $c \to \infty$, $\bar{W}_q^{(k)}$ also converges toward the same limit. Thus, the M/M/C queue is a good approximation for the $M/E_k/C$ queue, when c is large, at least as far as the average waiting time is concerned.

Notice that the same conclusion is not necessarily valid if the service time is described by a hyper-exponential distribution. Nevertheless, for large c, one would expect the error to be small.

4. The GI/G/1 Queue

4.1 The Pollaczek-Khintchine Equation for the M/G/1 Queue

The average waiting time in queue can be easily computed for the M/G/1 queue by employing the Pollaczek-Khintchine formula (Saaty [12], Chapter 2, Section 2-5b):

$$\bar{W}_q = \frac{\rho^2 + \lambda^2\sigma_T^2}{2\lambda(1 - \rho)} \tag{35}$$

where σ_T^2 is the service time variance and λ is the mean arrival rate. Recalling that $\rho = \lambda/\mu$ and that $\mu = 1/\bar{T}$, where $\bar{T}$ is the average service time, then (35) can be written the following way:

$$\bar{W}_q = \frac{\bar{T}}{2} \frac{\rho}{1 - \rho} [1 + C_V^2(T)] \tag{36}$$

The above equation is valid for any service time distribution, but only for Poisson input and one channel.

For the $M/E_\infty/1$ queue one has $C_V(T) = 0$, leading to:

$$\bar{W}_q^{(\infty)} = \frac{\bar{T}}{2} \frac{\rho}{1 - \rho} \tag{37}$$

For the M/M/1 queue one has $C_V(T) = 1$, which yields:

$$\bar{W}_q^{(1)} = \bar{T} \frac{\rho}{1 - \rho} \tag{38}$$

Therefore the $M/E_\infty/1$ queue presents an expected waiting time equal to half the average waiting time of the M/M/1 queue.

The Pollaczek-Khintchine equation is very useful when one has just a one-station problem. Unfortunately that is not the case in most of the real problems.

4.2 Extension of the Pollaczek-Khintchine Formula to the GI/G/1 Queue

An extension of the Pollaczek-Khintchine formula was obtained by Marshall [4,5]:

$$\overline{W}_q = \frac{(1 - \rho)^2 + \lambda^2(\sigma_t^2 + \sigma_T^2)}{2\lambda(1 - \rho)} - \frac{E[I^2]}{E[I]} \tag{39}$$

where σ_t^2 is the variance of the interarrival times, σ_T^2 is the service time variance and I is the service idle time. For the M/G/1 queue, Marshall's result agrees with the Pollaczek-Khintchine formula.

For practical applications expression (39) is not easy to handle due to the difficulty in getting the distribution of the idle times (I). Because of this, Marshall [5] obtained upper and lower bounds that are easy to apply:

$$J - \frac{(1 + \rho)}{2\rho\mu} \leq W_q \leq J \tag{40}$$

$$\text{where} \quad J = \frac{\rho\mu}{2(1 - \rho)} (\sigma_t^2 + \sigma_T^2) \tag{41}$$

Let us call f_G the ratio of the waiting time computed through (40) and W_q obtained through (36). Then one has:

$$\frac{\frac{C_v^2(t)}{\rho^2} + C_v^2(T) - (\frac{1}{\rho^2} - 1)}{1 + C_v^2(T)} \leq f_G \leq \frac{\frac{C_v^2(t)}{\rho^2} + C_v^2(T)}{1 + C_v^2(T)} \tag{42}$$

It can be easily seen that as $\rho \to 1$ the limiting band width for f_G approaches zero. At the limit one has:

$$\lim_{\rho \to 1} f_G = \frac{C_V^2(t) + C_V^2(T)}{1 + C_V^2(T)} \tag{43}$$

This means that the above results, as expressed by relation (42), can be used with reasonable confidence for situations in which ρ is high.

Thus, for the GI/G/1 queue one can use the following approach to compute the expected waiting time:

(a) Compute the waiting time using the Pollaczek-Khintchine equation (36).

(b) Compute a corrective coefficient f_G given by:

$$f_G = \frac{\frac{C_V^2(t)}{\rho^2} + C_V^2(T)}{1 + C_V^2(T)} \tag{44}$$

(c) Multiply the result obtained in (a) by f_G.

(d) In order to evaluate the error involved, compute through (42) the lower bound and estimate the approximate error through:

$$\varepsilon \simeq 2 \cdot \frac{f_{max} - f_{min}}{f_{max} + f_{min}} \tag{45}$$

where f_{max} and f_{min} are the upper and lower bound for f_G. Relation (45), combined with (42), yields:

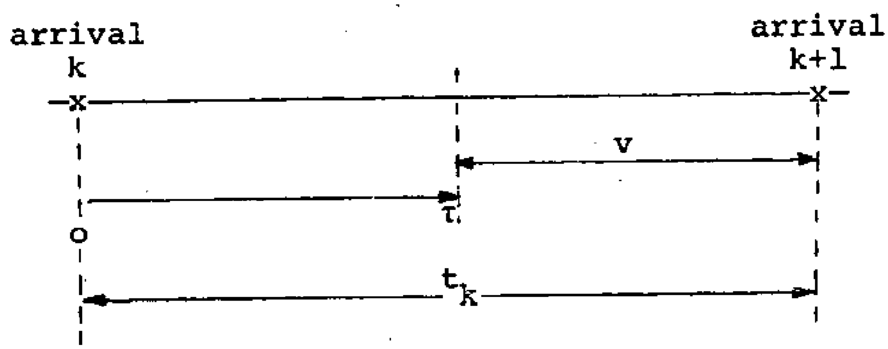
$$\varepsilon \simeq \left| \frac{\frac{1}{\rho^2} - 1}{\frac{C_V^2(t)}{\rho^2} + C_V^2(T) - \frac{1}{2}\left(\frac{1}{\rho^2} - 1\right)} \right| \tag{46}$$

The error approaches zero as $\rho \to 1$ which is a very good property indeed as far as the practical applications are concerned.

4.3 Validity of the Results

In order to understand the validity of the results described in Section 4.2, let us set forth the basic assumptions made by Marshall.

Let t be the distribution of the interarrival times, which are supposed to be independent (and equally distributed). Suppose we set the origin of time τ to coincide with an arrival.



Let v be the time to next arrival, which is, in general, a function of τ.

For exponential interarrival distribution one has:

$$E[v] = E[t] \tag{47}$$

For other distributions, like Erlang or deterministic,

$$E[v] \leq E[t] \tag{48}$$

Marshall's results are valid for interarrival distributions for which relation (48) holds. This happens in most cases, as for instance, the exponential, Erlang, deterministic distributions, etc. It is not valid, however, for the hyper-exponential interarrival distribution (which, in our kind of problems, is not likely to happen).

5. The GI/G/C Queue

Bounds for the GI/G/C queue were obtained recently by Brumelle [1].

A lower bound for the waiting time in the queue is given by:

$$\overline{W}_q^{(c)} \geq \overline{W}_q^{(1)} - \frac{E[T^2]}{2\overline{T}} \left(1 - \frac{1}{c}\right) \tag{49}$$

where $W_q^{(c)}$ and $W_q^{(1)}$ stand for the expected waiting time for the GI/G/C and the GI/G/1 queue respectively.

By making some algebraic transformations in (49) one gets finally:

$$\overline{W}_q^{(c)} \geq \overline{W}_q^{(1)} - \overline{T} \, \frac{[C_V^2(T) + 1]}{2} \left(1 - \frac{1}{c}\right) \tag{50}$$

Thus it is possible to determine a lower bound for the GI/G/C queue by applying the process described in Section 4.2 and then using relation (50).

Brunelle [1] also gives an upper bound for W_q:

$$\overline{W}_q \leq \frac{\operatorname{var}\left(\frac{T}{c} - t\right) + E(T^2)\left(\frac{1}{c} - \frac{1}{c^2}\right)}{-2\,E\left(\frac{T}{c} - t\right)} \tag{51}$$

which, after transformations, leads to:

$$\overline{W}_q \leq \overline{T} \cdot \frac{\rho^2 C_V^2(T) + C_V^2(t) + \rho^2 [C_V^2(T) + 1](c - 1)}{2\rho c(1 - \rho)} \tag{52}$$

For the D/D/C queue, for example, $C_V(t) = C_V(T) = 0$ and therefore one has:

$$\overline{W}_q \leq \frac{\overline{T}}{2} \cdot \frac{\rho}{1 - \rho} \, \frac{c - 1}{c} \tag{53}$$

The above expression has a very important practical implication: the limit for W_q as $c \rightarrow \infty$ coincides with the result obtained by applying the Pollaczek-Khintchine formula, as given by expression (36). This means that, for large c, the arrival distribution is not really important if the service time is kept reasonably constant.

6. Conclusions

As far as the queuing models are concerned, port terminals can be classified in two major categories:

(a) Conventional ports, in which the cargo is handled in relatively small amounts and vessels arrive usually in a random way. The typical example is the break-bulk conventional cargo ship terminals. If the number of berths is relatively large, one can apply the M/M/C queue model with good results due to the conclusions reached in Section 3.2.

(b) Specialized, fast turnaround time terminals, such as oil and bulk terminals in which case the Poisson arrival assumption is not usually valid due to the high degree of organization in ship scheduling and operation (fewer number of large ships that can keep a reasonably constant schedule pattern).

For large c, however, the results of Section 5 indicate that the arrival distribution is not very important, provided the service time is reasonably constant.

Therefore, even if the analyst does not know the interarrival time distribution, it is possible to get a good estimate of the average waiting time by assuming Poisson input.

The conclusion we reach at this time is that the classical queuing models give good estimates for large values of c. Of course this is a conclusion that should be regarded with some reserves, since the state of the art in queuing theory at present still suffers from a lack of a basic structural framework. Let us hope that within the next few years the results to be obtained in research in this field will provide us with more tools to tackle this type of problem.

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APPENDIX C

A WORKING

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A

WORKING

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I. Port Related

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2. Agerschon, H., Koresgaard, S. "System Analysis for Port Planning", Abstracted Dock and Harbour Authority V. 49 N. 581 March 1969 pp 411-15/Queuing analysis - assumption: long stretch of berth with fairly high number of average size berths where waiting ship will always fit into first available berth. A smaller number of berths which will all accommodate any ship which calls. (GPSS)

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Factors which govern type, location and capacity of ports required in immediate future.

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Three questions arise whenever congestion occurs. The first question concerns the optimal use of a facility (the economic capacity). This question might be answered by a system of tolls or subsidies which equate private to social cost. To illustrate the analysis the social cost of adding a tow to the waterway was calculated, and the toll which would cause the tow operater to face social cost was determined. The second question concerns the decision to expand physical capacity (when is demand sufficiently large to justify expansion). This might be measured by a B/C analysis of the expansion decision. For example, the benefit of expanding the lock is the reduction in total locking time. If this dollar benefit exceeds cost of expansion, physical capacity should be increased. Third question concerns the effect of toll (or its absence) on the character of service demanded (the amount of service time demanded by a single customer). This question might be answered by noting that congestion results from the amount of service time demanded by a customer. Thus, the optimal toll should depend on actual service time.

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23. Fratar, T. V., Goodman, A. S. and Brant, A. F., "Prediction of Maximum Practical Berth Occupancy, <u>Transactions</u>, ASCE, Part IV, Vol. 176., Harvard Brookings Model.

II. <u>Other</u>

1. Babb, E. M., Yu, H. H., "Analysis of Factors Affecting Least-Cost Size of Plant, <u>Management Science</u>, V. 16, No. 10, June 1970, pp. 607-13.

A general model used to analyze the effect of assembly and distribution factors and economies of scale in processing on least-cost size of plant and on cost components is described. Applied to fluid milk plants and county elevators appear unit cost decreasing.

2. Charmil, C., Thedie, J.,Odir, L., Permanent Int'l. Assoc. Road Congress Proceedings; XIIIth Congress, Tokyo, VII-6, re pp., 8 Fig., 3 Tables.

The principles are reviewed for the calculations of rates of return used in France in the choice of Highway investments. They consist in comparing the cost of investments with their advantages, divided as follows: user surplus, non-user surplus, and state surplus. A review is presented of the influence on the highway network on the economic development and improvement of the territory. A French method is reviewed for comparing the economic advantages brought about by different programs of investment, comprising differences of alignment and technical characteristics. The model supposes a generation of traffic according to a gravity model. A systematic study of economic capacities is presented by the authors to show that this capacity depends not only on the existing state of the highway, but also on its state after the work and the cost of these works. Two hypotheses in highway policy, characterized by the rate of return of investments are retained. In each of these hypotheses, the report determines what is the economic capacity of each type of highway, then the optimum sequence of investments. This optimum sequence is entirely defined by the initial traffic on the highway. General rules concerning the role of each type of road are evolved from the study.

3. Conway, E., "Transportation and Planning - Some Myths Revisited", Canadian Good Roads Association Process,

Economic myth, relative capacity myth, relative efficiency.

4. Dupuis, T. M., Jen, F. C., Pegels, C. C., "Optimal Capacities of Production Facilities", Mgmt. Science V. 14, No. 10, June 1968, pp. B-573-80

General cost model and methods of solution for determining optimum combinations of capacities of production facilities of steady-state production systems. Model is applied to practical problems of finding optimum combinations of capacities of production facilities of oxygen production facilities and inventory system.

Objective function of formulated model is very complex non-linear function of two decision variables, oxygen production rate and oxygen storage pressure.

Computerized gradient method is used to find optimum value of two decision variables, using parameter values that have been determined empirically; effect of variations in some of parameter values on optimum values of decision variables.

5. Funk, M. L., Shell, R. R., Wang, J. J., "Toward Solution for Optimal Allocation of Investment in Urban Transportation Networks", National Research Council - Highway Research Board - Res. Record No. 238- 1968 23-45.

Application of discrete version of maximum principle to problems of optimal investment in transportation networks; network investment problems that include non-linear relationships among travel time, traffic volume and investment all considered; technique determines optimal investment policy in network and on this basis assigns given trip demand to improved network. Objective is to provide investment policy that will cost least to construct and operate.

6. Goldim, K. D., "Three Aspects of Highway Efficiency Amount, Quality and Price," Journal Transport Economics and Policy/UK/, Sept. 1968, Vol. 2, No. 3, pp. 349-66.

Highway efficiency involves efficient pricing (short run) of efficient amount of highway (long run) to achieve efficient quality of service. Section I Amount & Pricing; Sect. II Quality, Money Value can be assigned to highway user's time employing an eff quality for new highways.

7. Howard and Nemhauser, 1968, Johns Hopkins, Baltimore, "Optimal Capacity Expansion", Naval Res. Logistics Quarterly, V. 15 N. 4, pp. 535-550, December 1968.

Temporal expansion of capacity of plant or road given estimates of its desired demands are given. Basic problem: Given a sequence of predicted demands for N time periods, determine the optimal investment decision in each period to minimize a linear investment cost and a strictly convex cost of capacity. The relationship between capacity and the investment dimension is assumed to be linear but time varying. Constraints on both the individual decision and sum of decisions are considered. Algorithm is derived.

8. Morlok, E. K., "The Comparison of Transport Technologies", Highway Res. Record, The Res. Board, No. 238, pp. 1-22, 7 Fig.

Literature review and research to develop a framework of quantitative measures and relationships to permit the direct comparison of the properties of diverse transport technologies. Interest for comparative purposes focused on two areas: 1) the cost property, 2) the properties of the transport service provided. Research is concerned with the identification and quantification of measure of output capability and the relation of these to technological properties of the system.

Applied N.E. corridor - dimensions form transport system output space - generalized transport cost model was developed in which fixed and marginal costs were associated with each of the functional elements of vehicular transport system. General cost - output space developed within which technologies can be compared.

9. Vickery, W., "Optimization of Traffic and Facilities", J. Transp. and Economic Policy, May, 1967, 1, 123-36.

10. Vickery, William S., "Congestion Theory and Transport Investment", Am. Economic Rev., Vol. 59, No. 2, pp. 251-260, May, 1969,

Investment in transport facilities necessarily begins by being largly investment in the provision of new routes or new services under conditions of substantial indivisibilities and increasing returns to scale. As investment proceeds, however, larger and larger payments of transp. investment are made primarily, or at least in large measure, to relieve congestion on existing routes and to expand overall capacity. It is in this later type of investment, designed to relieve congestion with which paper is concerned. For purposes of economic analysis, six types of congested situations are distinguished and discussed and congestion control through pricing is analyzed.

APPENDIX D

NUMERICAL EXAMPLE OF SIMPLIFIED DYNAMIC SEAPORT ALGORITHM

NUMERICAL EXAMPLE OF SIMPLIFIED DYNAMIC SEAPORT ALGORITHM

The following example illustrates the operation of the dynamic programming algorithm of chapter 5. Allocation to berth space has been neglected for simplicity. The recursion relation is then:

$$C_n = \underset{\{t_n\}}{\text{Min}} \left[C_{n+1} + q_n + f_n - h_n + \lambda d_n\right]$$

We shall assume:

$$q_n = d_n/t_n$$

$$f_n = t_n - t_{n-1}$$

$$h_n = d_n$$

$$d_n = 2d_{n+1} - t_n$$

$$\lambda = 0$$

$$tmax = 3$$

$$M = 3$$

$$d_3 = 5$$

$$t_o = 2$$

<u>State 3</u>

$$C_3 = \underset{t_3 \geq t_2}{\text{Min}} \left[0 + 5/t_3 + t_3 - t_2 - 2.5 + t_3\right]$$

Suppose $t_2 = 1$:

then $t_3 = 1 \rightarrow C_3 = -4$

$t_3 = 2 \rightarrow C_3 = -4.5$

$t_3 = 3 \rightarrow C_3 = -3.33$

Suppose $t_z = z$:

then $t_3 = 2 \rightarrow C_3 = -5.5$

$t_3 = 3 \rightarrow C_3 = -5.33$

Suppose $t_3 = 3$

then $t_3 = 3 \rightarrow C_3 = -6.33$

The optimal policy table stored is thus:

t_2	C_3	$t_{3opt.}$	d_z
1	-4.5	2	8
2	-5.5	2	8
3	-6.33	3	7

<u>**Stage 1**</u>

$$C_2 = \underset{\{t_2 > t_1\}}{\mathrm{Min}} \quad \{C_3(t_3(t_2)) + \frac{d_z(t_2)}{t_2} + t_2 - t_1 - 2d_2(t_2) + t_2\}$$

Suppose $t_1 = 1$:

then $t_2 = 1 \rightarrow C_2 = -11.5$

$t_2 = 2 \rightarrow C_2 = -14.5$

$t_2 = 3 \rightarrow C_2 = -5.0$

Suppose $t_1 = 2$:

then $t_2 = 2 \rightarrow C_2 = -15.5$

$t_2 = 3 \rightarrow C_2 = -6.0$

Suppose $t_1 = 3$:

then $t_2 = 3 \rightarrow C_2 = 7$

t_1	C_2	.	
1	-14.5	2	
2	-15.5	2	15
3	- 7.0	3	11

Stage 1:

$$C_1 = \underset{\{t_1 > 2\}}{\text{Min}} C_2(t_2(t_1)) + \frac{d_1(t_1)}{t_1} + t_1 - t_o - 2d_1(t_1) - t_1\}$$

$t_o = z$, so:

$$t_1 = 2 \rightarrow C_1 = -36.5$$

$$t_1 = 3 \rightarrow C_1 = -21.33$$

so the optimal allocation is:

t_o	C_1	$t_{1opt.}$	d_o
2	-36.5	2	28

If the initial demand happened to be $d_o = 28$, we would now have the answer. If not, we would attempt to arrive at $d_o = d_o$ (required) by inserting a longrange multiplier.

$$C_N = \text{Min} \quad \{C_{N+1} + q_N + f_N - h_N + \lambda d_N\}$$

The optimal value of t_N at each step would correspond to a small demand d_N if λ were large. The correct value of λ would produce the correct value of d.

If d_o = 28 were the correct value, than the optimal schedule is clearly given by:

$$t_o = 2$$

$$t_1 = 2$$

$$t_2 = 2$$

$$t_3 = 2$$

This says that because $L_{MAX} = 3$, we cannot add enough capacity to maintain the initial demand, and adding one unit (t = 3) will cost more to install than it will raise profit.

PROGRAM DOCUMENTATION

A program listing and flow chart appear on the following pages.

Definitions of program variables are listed below:

csemp	cost of empty tank per unit time
shcst	cost of delaying a ship per unit time
shcap	capacity of ships
disrt	discharge rate of ships
outfl	rate at which tank is emptied from land-side.
dt	time increment
tkcap	tank capacity
cstank	maintenance cost of tank, per unit volume per unit time
zmean	mean ship inter-arrival times
time	time
capac	instantaneous quantity of oil in ship which is currently unloading
tklev	instantaneous quantity of oil in tank
flow	rate of flow between ship and tank
cost	cost per time increment
cmcst	cumulative cost
cmcstr	average cost per unit time
raw	table of ship inter-arrival times
arrtm	table of ship arrival times

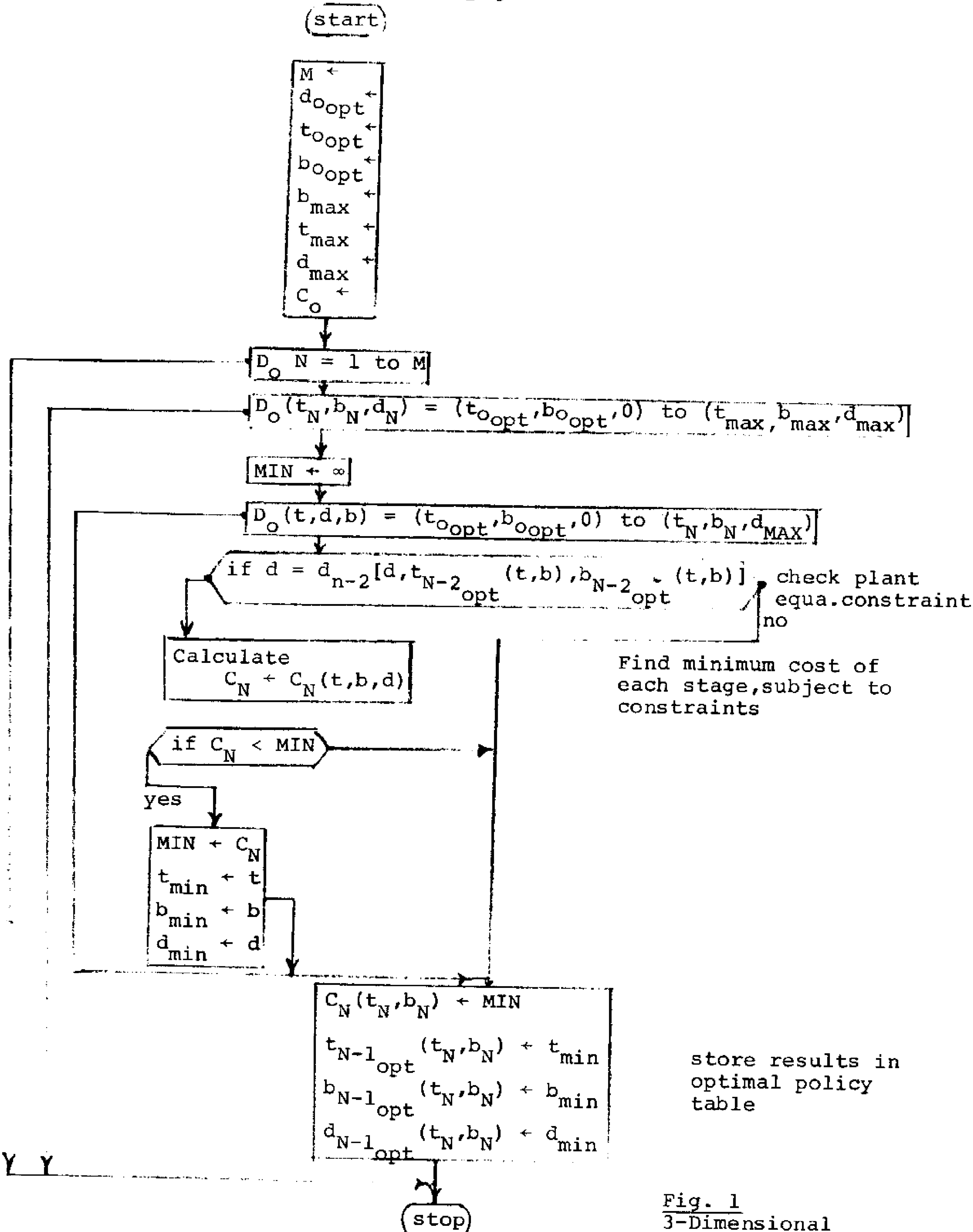


Fig. 1
3-Dimensional Algorithm

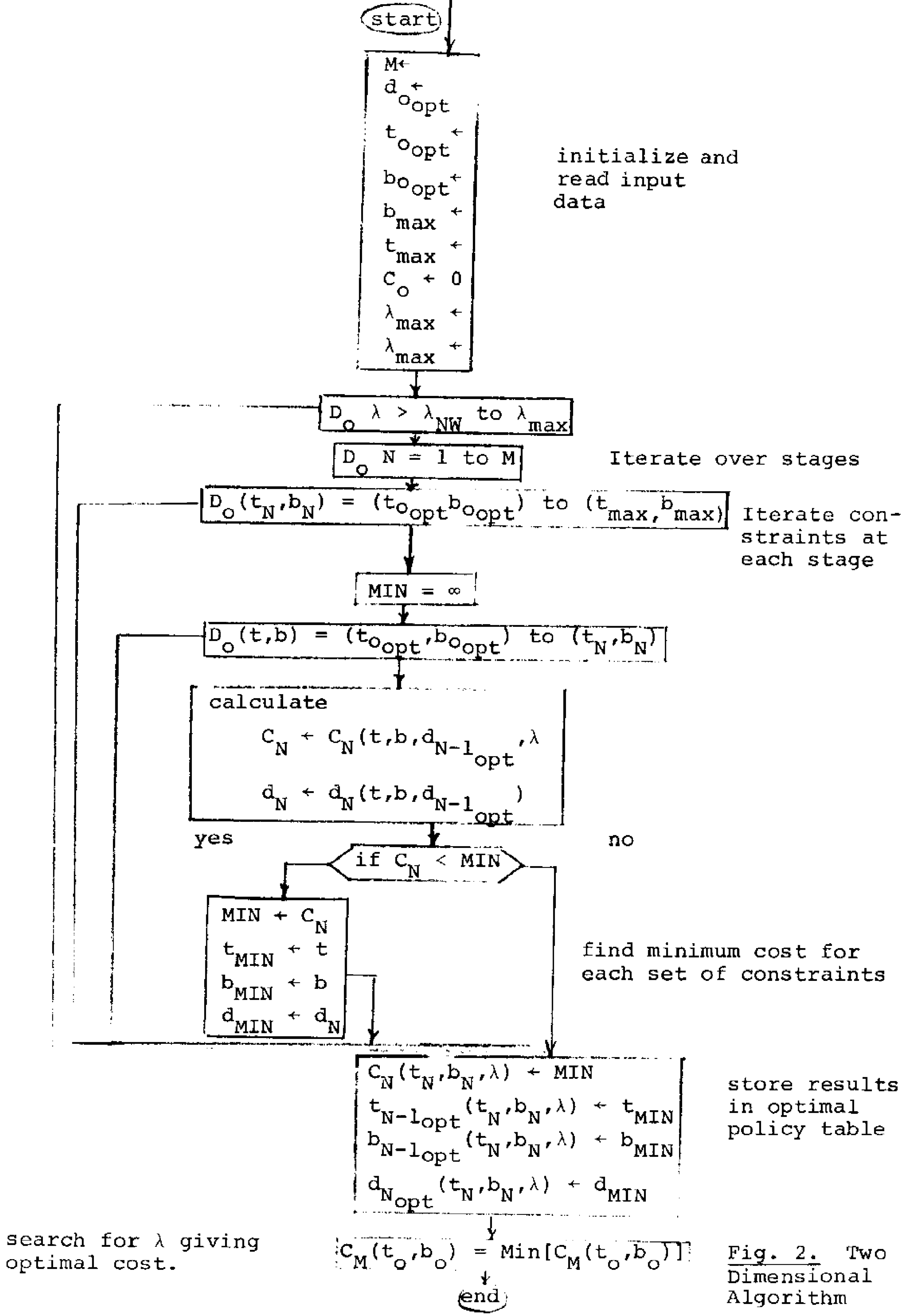
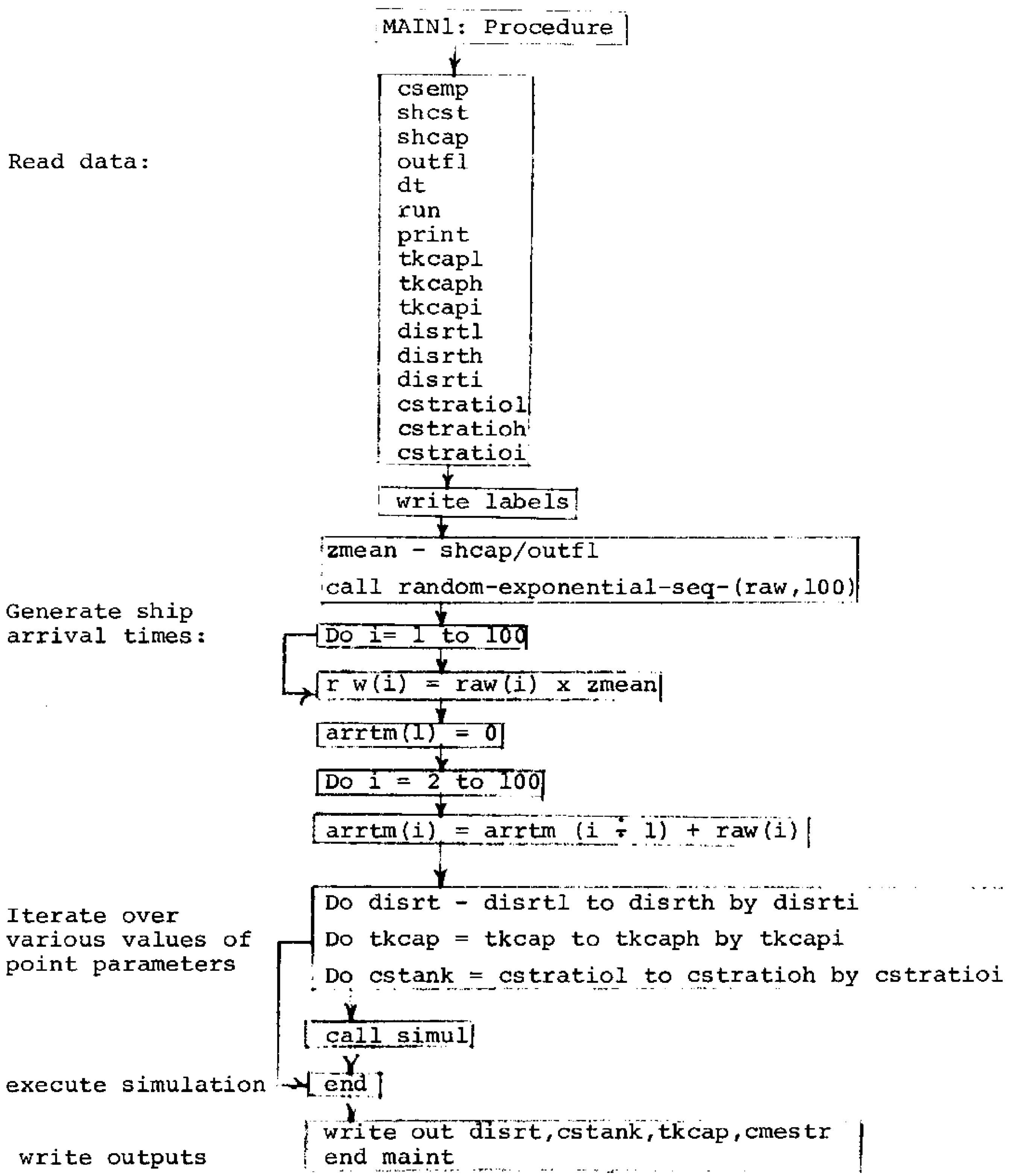
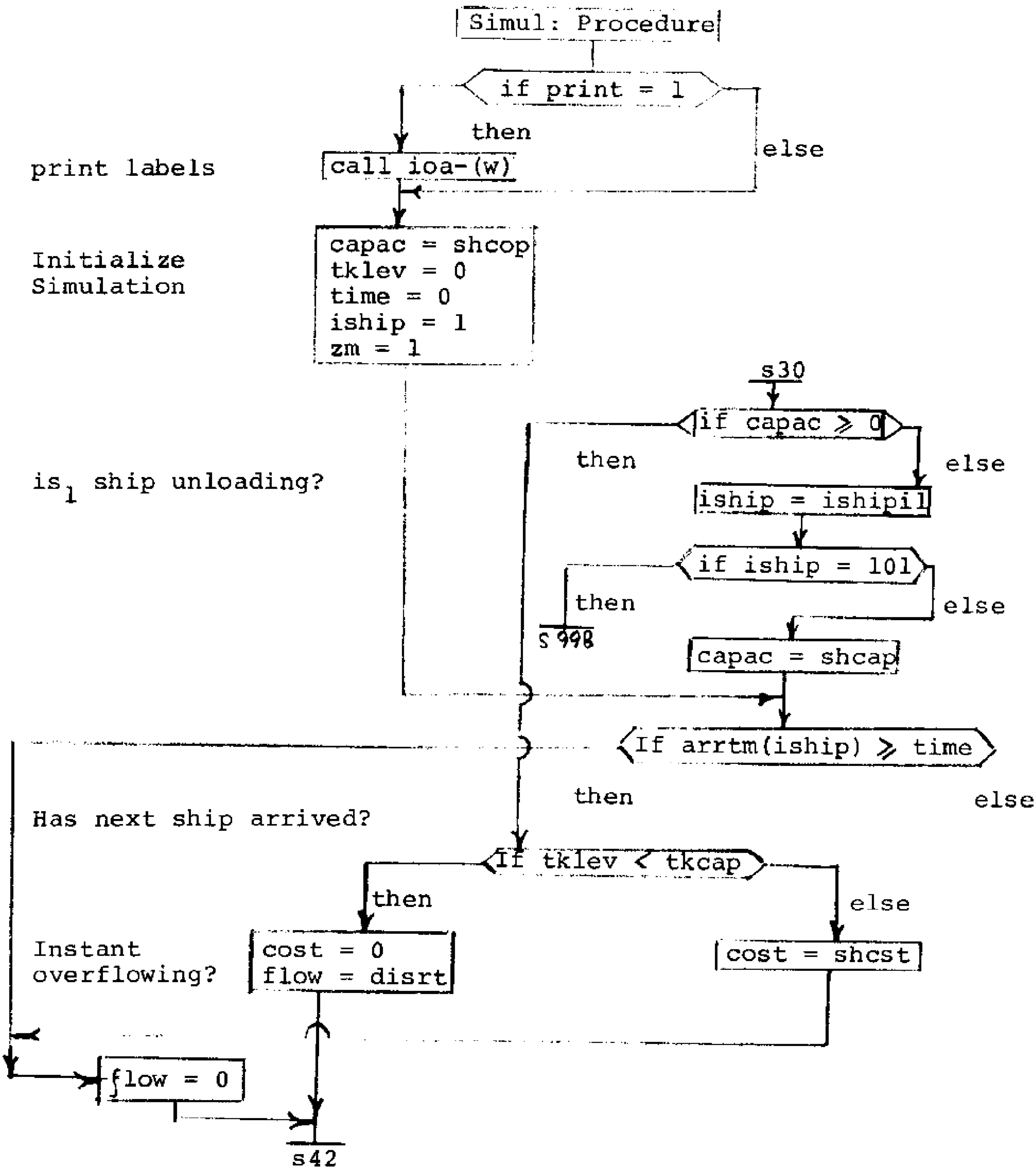


Fig. 2. Two Dimensional Algorithm

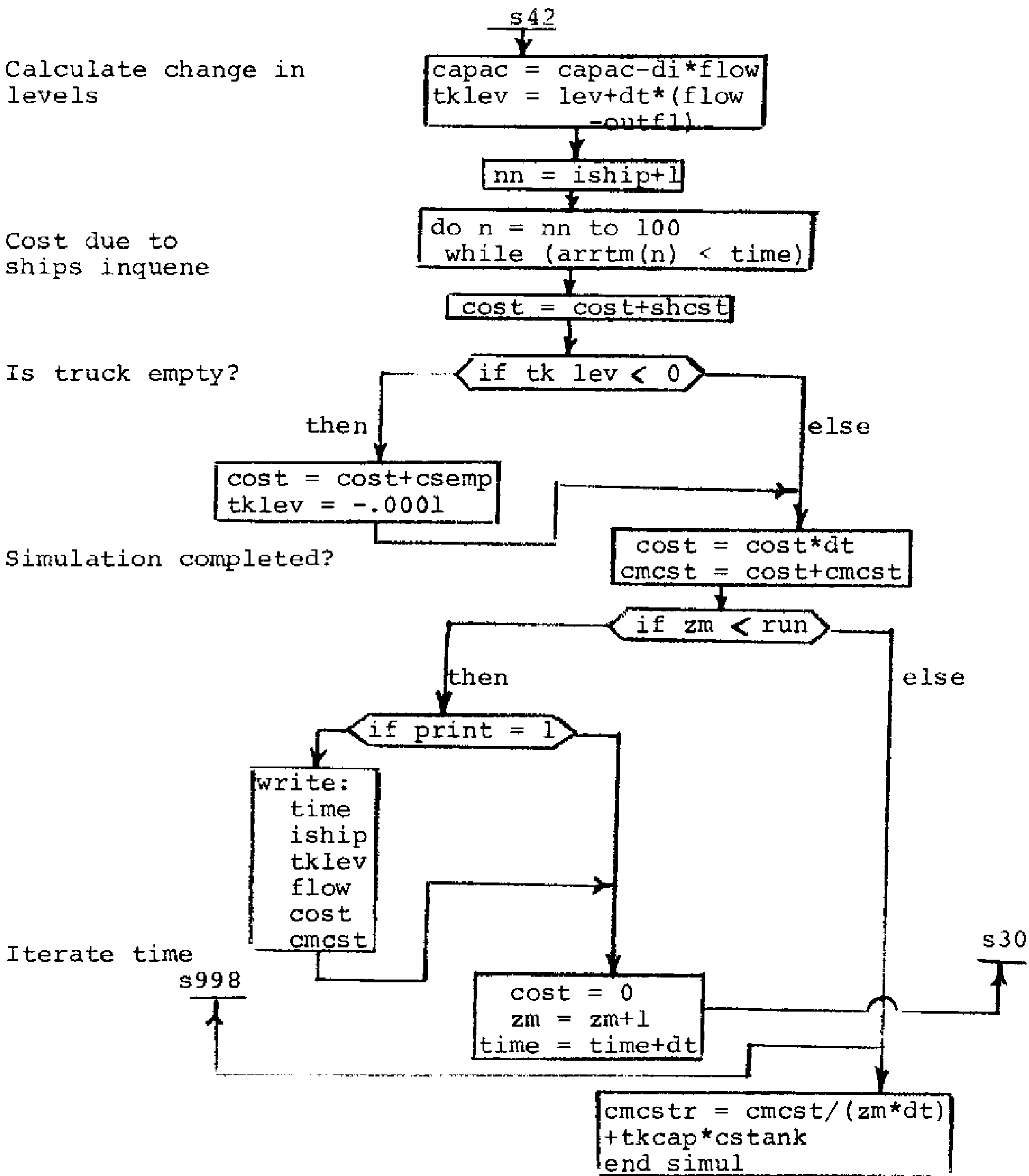
MAIN1: FLOWCHART



SIMUL: FLOWCHART



SIMUL FLOWCHART (cont'd)



```
print main1.list

     main1.list     01/12/71  2232.2 est Tue


0014 COMPILATION LISTING OF SEGMENT main1
     Compiled by: Multics PL/I Compiler, Version of 6 January 1971.
     Compiled on: 01/12/71  2219.0 est Tue


main1:    procedure ;
     declare   raw(100),
          arrtm(100);
     /*   read input data*/
     call ioa_("NTER VALUES FOR CSEMP,SHCST,SHCAP,OUTFL:");
     call read_list_(csemp,shcst,shcap,outfl);
     call ioa_("NTER VALUES FOR DT,RUN,PRINT:");
     call read_list_(dt,run,print);
     call ioa_("ENTER LIMITS AND INCREMENT FOR TKCAP,DISRT,CSTANK:");
     call read_list_(tkcapl,tkcaph,tkcapi,disrtl,disrth,disrti,
          cstratiol,cstratioh,cstratioi);
     call ioa_("  DISCH RATE   TANK COST    TANK CAP  COST RATE");
     zmean=shcap/outfl;
/*   generate ship arrival times*/
     call random_$exponential_seq(raw,100);
     do i=1 to 100 by 1;


          raw(i)=raw(i)*zmean;
          end;
     arrtm(1)=0;
     do i=2 to 100 by 1;
          arrtm(i)=arrtm(i-1)+raw(i-1);
          end;
     do disrt=disrtl to disrth by disrti;

     do tkcap=tkcapl to tkcaph by tkcapi;
     do cstank=cstratiol to cstratioh by cstratioi;
     call simul;
```

```
 simul:   procedure;
/*   initialize simulation*/
     if print=1
          then call ioa_("     TIME      SHIP     SHIPL     TANKL      FLOW      COST      CMCST");
          else;
     capac=shcap;
     tklev=0;
     cmcst=0;
     time=0;
     iship=1;
     zm=1;
     go to s32;
/*   initialize new ship*/
s30: if capac¬<0         /* Is ship empty yet?*/
          then go to s33;
          else do;
               iship=iship+1;
               if iship=101    then go to s998;
               else;
               capac=shcap;
               end;
s32: if time < arrtm(iship)       /*has next ship arrived yet?*/
          then go to s41;         /*no*/

          else  s33:     if tklev<tkcap     /*yes, but is tank overflowing?*/
               then do;     /* no overflow*/
                    cost=0;
                    flow=disrt;
                    end;
               else do;       /* overflow*/
                    cost=shcst;
                    flow=0;
                    end;
                    go to s42;
s41: flow=0;
```

```
/*          calculate change in levels */
s42:        capac=capac-dt*flow;
 tklev=tklev+dt*(flow-outfl);
/*          calculate cost due to ships in queue*/
 nn=i ship+l;
 do n=nn to 100 by 1 while (arrtm(n) < time);
                               cost=cost+shost;
                               end;
s43:         if tklev<0
             then do;
                       cost=cost+csemp;
                       tklev= -.0001e0;
                       end;
             else;
s45          omcst=omcst*cost*dt;
/*           iterate time and make outputs */
 if zm<run
             then do;
                       if print=1
                               then call ioa_( "9.2f^9d^9.2f^9.2f^0.2f^9.2f",
                                         time,iship,capac,tklev,flow,cost,cmcst);
                               else;
             cost=0
                       zm=zm+1;
                       time=time+dt;
                       go to s30
                       end;
             else go to s998;
s998:        cmcstr=cmcst/(zm*dt)+tkcap*cstank;
 end simul;
call ioa_("^12.4f^12.4f^12.4f^14.4f",cstank,tkcap,cmcstr);
end;
end;
end;
s999:       end mainl;
EOF
```

APPENDIX E

PORT PRICING AND EXPANSION

by

J. W. Devanney III

L. H. Tan

1. Introduction

The relation between the necessary conditions for the efficient short-run allocation of resources (marginal cost pricing) and the necessary conditions for long-run efficiency (attracting the appropriate levels of capital) has long been a bone of contention. In the past, it has often been alleged that in a large number of situations of practical interest, the two principles are inconsistent. This argument has been applied with pernicious effect in the marine transport industries, among others. Those who have argued that the principles governing short-run efficiency and long-run efficiency are not inconsistent, while to our mind entirely persuasive, have not, in our opinion, placed their arguments on firm quantitative foundations.

The purpose of this paper is to offer a demonstration based on a reasonably general model that for all but entirely pathological situations, short-run allocative efficiency and long-run are not only not inconsistent, but are intimately and necessarily tied together. A byproduct of this demonstration is a quantitative method for both the short-run and long-run regulation of monopolies. There has been much confusion in this area, once again under the impression that marginal cost pricing will lead to less than normal return on investment in the face of large fixed investments.

The vehicle which we will use to present our arguments is port pricing and expansion. This is a product of the authors' particular research interests. Fortunately, however, this example combines all the elements required to demonstrate how short-run pricing and timing and level-of-investment decisions can be coupled to generate both short-run and long-run efficiency. The translation to other areas of application will be obvious to the reader.*

We will begin with a situation in which the interaction between short-run pricing and investment timing is particularly clear-cut: port pricing and expansion under the objective of maximum private profits. While we hold little brief for this particular objective, this problem will serve to demonstrate the basic line of reasoning which will be used throughout. Secondly, we will move to a delineation of port pricing and expansion under the objective of maximum world income - more precisely, Pareto-optimality with respect to prices prevailing outside the port. Thirdly, we will indicate the modifications required when the objective is maximum national income. Finally, with some numerical examples and the aid of partial equilibrium analysis, we will compare the policies generated by the above arguments with the "average cost" policies typically followed by public and semi-public monopolies.

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*One cautionary note: the argument which we will develop assumes that changing prices is costless. In situations such as urban mass transit management, this hypothesis may require some modification.

2. Monopoly Profit Maximization

The first objective function which we will examine is monopoly profit maximization. For a variety of reasons, the operation of a particular port almost always ends up under the control of a single entity, usually some public body. Such centralization implies that the controlling body has a degree of monopoly power over the shippers and hinterland that it serves. Thus, a possible objective function for such a port is to operate in such a manner as to maximize the present value of the differences between its revenues and its outlays.

Our investigation of this objective function does not necessarily mean that we recommend it. However, it is a possible objective function. It also represents one end of the spectrum of objective functions we will study. And it also turns out to be the easiest to analyze - therefore, for pedagogic reasons we will tackle it first.

The basic model

In analyzing all our objective functions, we will consider the following extremely simple port:

1) The port offers a single, homogeneous cargo-handling service. That is, we might imagine a completely specialized port which handles only one commodity. The amount of cargo-handling services performed by the port in some time period, n, can be measured by the throughput of this commodity in this period, x_n, in, say, tons. Since we have assumed that the port's

services are homogeneous, the port's pricing policy through time can also be described by a single number, p_n, in, say, \$/ton. For exposition's sake, we will assume that the period in question is a year, although it could just as easily be a month or a season. Further, we will assume that the period is short enough so that the port is willing to act as if demand were constant over this period.

2) At discrete points in time, say once a year, the port has the opportunity to expand. However, the port has only one such expansion opportunity at such a time. To wit, it can increase the design capacity, C_n, of the port by ΔC tons by making an outlay of $EC(C_n)$ dollars or it can choose to make no change in design capacity at this time.* That is, we might imagine a port whose only expansion alternative is to, once a year, add another berth of design capacity ΔC. We will assume that if the port decides to expand at the beginning of the nth period, t_n, the berth will become available at the

*More precisely, the expansion cost, $EC(C_n)$, is the present value of the time stream of expenses to which the port commits itself when it decides to make the expansion, including any future maintenance costs which are independent of throughput. Notice that the expansion cost can depend on the present installed capacity; thus, we can accommodate both economies and diseconomies of scale.

end of that period. We will also assume that any such investment will last forever.*

3) Let $VC(x_n, C_n)$ be the throughput-dependent expenses associated with moving a quantity x_n in period n given an installed design capacity of C_n at that time. We will assume that VC is a non-increasing function of C_n and that its derivative with respect to x_n, $MC(x_n, C_n)$, is a non-decreasing function of x_n. For ports, for a given C_n, marginal cargo-handling cost is generally constant up to some level, whereupon it increases sharply, finally becoming vertical at the point where it is impossible to further increase throughput. At this point, the marginal cost to the port of handling a unit of cargo becomes the maximum that a turned-away unit of cargo would have been willing to pay for this service. Thus, our concept of marginal cost includes the "congestion cost" of Allais, reference [1].

4) Finally, we will assume that the demand for the port's service in periodn, $D(p_n, t_n)$, is a function only of the price in that period and time. In many respects, this is the most limiting assumption of all. In real life, the port's pricing policy through time will affect the long-run growth in demand either through long-run adjustments by

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*Finite investment life can be accommodated by the basic reasoning we will use without conceptual difficulty. However, finite life involves some rather severe computational problems.

shippers or by encouraging the development of competing ports whose existence will then affect the demand perceived by the monopolist. Our assumption that the growth in demand is unaffected by past pricing policies rules out these phenomena.

A dynamic program for obtaining the optimal pricing-expansion policy

We will assume that the port's cost of capital is constant at r% per annum and will denote the associated discount factor by ρ. The demand surface through the future, $D(p,t)$, is known and the monopolist is willing to assume that demand is constant through an individual period - a year in our case. That is, he is willing to act as if demand makes a discrete shift to the right at the end of each period and then remains constant through the ensuing period.* This implies that the short-run profit maximizing price will be constant through an individual period.

At the beginning of the nth period, t_n, the port's current situation is completely described by the amount of design capacity already installed, C_n. Define $V_n(C_n)$ to be the maximum present valued profits obtainable from t_n on, if at t_n the port has C_n units of design capacity operating.** At t_n in this situation, the port has two decisions to make:

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*This requirement can always by met by simply making the length of an individual period short enough. In port problems, one will rarely have to go to a period of less than a quarter and in many cases a period of a year or more will suffice.

**V_n is the present value profits present valued back to t_n.

1) How much should it charge for its services for the period t_n to t_{n+1}?

2) Should it order an expansion of ΔC at t_n or not?

Given a particular C_n at t_n, the two decisions can be separated, for any new expansion ordered at t_n will not become available until t_{n+1}. For this situation, it is well known that the monopolist will maximize his short-run profits by setting price such that marginal revenue equals marginal cost, that is, by solving the equation

$$(2.1) \quad \frac{\partial}{\partial x} [D^{-1}(x^*(C_n,t_n),t_n) \cdot x^*(C_n,t)] = MC[C_n,x^*(C_n,t_n)]$$

for $x^*(C_n,t_n)$ where D^{-1} is the inverse of the demand function. $D^{-1}(x^*(C_n,t_n))$ is the monopolist's profit maximizing price, $p^*(C_n,t_n)$, in this situation, and the resulting maximum net operating revenues for the period (t_n,t_{n+1}) are

$$(2.2) \quad R^*(C_n,t_n) = p^*(C_n,t_n) \cdot x^*(C_n,t_n) - VC(C_n,x^*(C_n,t_n))$$

These results hold whether or not the port decides to expand at t_n given C_n because of the construction delay.

Of course, price is not the only variable under the port's control. It also has control over the amount of design capacity installed. Once again, in the static situation, it is well known that a monopolist will maximize his long-run profit by investing in the amount of capacity such that when he charges the short-run monopoly profit maximizing price, he will be operating at the minimum point on his average cost curve.

The problem is that the port is not faced with a static situation. Typically, demand for the port's services will be growing, which means that the demand curve will be continuously shifting to the right through time.* In order to match this growth, the port would have to be continuously shifting the amount of design capacity. Unfortunately, design capacity generally only comes in discrete chunks. Due to subunit economies of scale it is usually not useful to consider building half a berth or buying half a crane. As a result, it is diseconomic to add design capacity in a completely continuous fashion. To illustrate this problem, we have assumed that our example port has only one expansion option: once each year it may purchase ΔC units of design capacity or none at all. There is no in-between.

Examining these two options: if the port decides not to expand at t_n given C_n, then the maximum present valued profits obtainable through the future present valued back to t_n is

$$R^*(C_n,t_n) + \rho V_{n+1}(C_n)$$

If, on the other hand, the port chooses to expand at t_n, then the present value of future profits assuming optimal operation from t_{n+1} on is

$$R^*(C_n,t_n) - EC(C_n) + \rho V_{n+1}(C_n + \Delta C)$$

The monopoly profit maximizing port will choose the maximum of these two options. Hence, we have the following recursion relation.

$$(2.3) \quad V_n(C_n) = \max\begin{cases} R^*(C_n,t_n) + \rho V_{n+1}(C_n) \\ R^*(C_n,t_n) - EC(C_n) + \rho V_{n+1}(C_n + \Delta C) \end{cases}$$

*The shift to the right in demand may have seasonal fluctuations superimposed on it which may temporarily move the demand curve to the left. As long as the general trend is to the right, these fluctuations present no problems for the analysis that follows.

which holds for all possible values of installed capacity, C_n, and for all possible n = 0, 1, 2, 3...; that is, for all possible decision points t_n. In order to be able to numerically solve this set of equations, we must assume a boundary condition on V_n at some time in the future. One such boundary condition follows from supposing that at some time in the relatively distant future, t_N, demand will cease to grow, in which case it will be optimal not to order any expansion after t_N, nor will the profit maximizing price change.

Let $R^*(C_N,t)$ be the resulting profit maximizing revenue obtainable in any period for which $t > t_N$ given that the installed capacity from t_N on is C_N. Since this amount is constant through the future from t_N on, the present value from t_N on given C_N is

(2.4) $$V_N(C_N) = R^*(C_N,t_N)/(1 - \rho)$$

yielding the boundary condition at time t_N in the future for all C_N. Starting with the boundary condition and employing backwards recursion, one can solve for the optimal value function for all $V_N(C_N)$ and the corresponding profit maximizing expansion and pricing policy.

<u>A sample problem</u>

A computer program implementing the above dynamic program has been written. We have exercised it on the following sample problem.

1) Demand linear in price with exponentially decreasing growth.

(2.5) $$D(p,t) = (1 - e^{-\gamma t})(\alpha - \beta p)$$

For all our sample exercises in this paper, we have held the demand surface constant, setting $\alpha = 10^6$

tons, $\beta = 10^4$ tons/\$ and $\gamma = .1$. This demand surface is shown in Figure 1. For this demand surface, price can run between \$100/ton and \$0/ton and the resulting throughput will be between 0 tons and a number which is zero at $t = 0$ but fairly rapidly approaches one million tons per year as t approaches 40 or so. For this demand surface, we have taken t_N to be 50 since practically all the growth has taken place by this time.

2) Marginal costs of each berth are identical and quadratic in throughput. Given identical marginal costs, the monopolist will distribute his throughput, x, evenly among each of the berths. Thus, at any time, (x/I) tons of cargo will be flowing through each berth, where I is the number of currently installed berths, $C/\Delta C$. The marginal cost function which was used in the sample problem was

$$MC(x,C) = \frac{3 \cdot EC(1 - \rho)}{2\Delta C^3} \left(\frac{x}{I}\right)^2 I \tag{2.6}$$

where the constant $1.5EC(1 - \rho)/\Delta C^3$ has been chosen to make the average cost curve minimum when throughput equals design capacity.*

This simple structure was chosen because it makes interpretation of the results easy. The basic algorithm, of course,

*This is a purely expositional convenience. The entire line of reasoning does not depend on the concept of a "design capacity" in any fundamental way. Nor does it depend on the concept of "average cost", which, strictly speaking, applies only to the steady-state situation.

can accept any demand function and cost structure meeting our rather general conditions.

Results

The results of these sample calculations for $\rho = .9$, $EC = \$1 \times 10^6$ and ΔC = 100,000 tons/year, 50,000 tons/year and 25,000 tons/year respectively are shown in Figures 2, 4 and 6 respectively. There are several things to notice about these figures. One is that price varies very little from the marginal revenue maximizing price, which is always $50/ton for our rather strange demand growth pattern. This is due to the much lower marginal costs. Except for Figure 6, where the monopolist cannot bring on capacity as fast as he would like, the price is practically unaffected by the present situation, remaining in the neighborhood of $51 - $53 throughout. The corresponding marginal cost is in the neighborhood of $2 or $3, except for Figure 6, where it moves to about $7/ton.

The profit maximizing monopolist alternates periods in which design capacity is higher than throughput with periods in which the reverse is true, <u>adjusting price downward every time he increases installed capacity</u>. It does not always pay the monopoly profit maximizer to delay expansion to the point where the expansion is immediately utilized at design capacity. The number of berths approximately doubles with each halving of the design capacity of each berth. As a result, the total throughput and the final situation are quite similar in each case, as is necessarily the case given the similarity in the prices charged. This occurs despite the fourfold increase in costs from Figure 2 to Figure 4 and the fact that no one would regard the demand structure of Figure 1 to be particularly inelastic. The reason why design capacity is not quite equal to throughput at steady state is that the port has only a finite number of design capacities available and thus the monopolist (program) is forced to choose the "closest" of the design capacities available. Given the parameters chosen, the port is a very profitable enterprise for all three cost structures.

In order to investigate behavior in a situation where the monopolist could not make as much money, we reran these three cases multiplying EC by 10. That is, a berth now costs $10 million. The results are displayed in Figures 8, 10 and 12. In these situations, the constraint of no more than one new berth per year is never limiting; the general level of his price is fairly constant throughout the period for each ΔC. However, since the monopolist no longer compensates for a halving of ΔC by doubling the number of berths, the level of this price now changes markedly with change in ΔC with a resultant effect on throughput. Notice that with the lower ΔC's the penalty for off design operation is so high that it pays the monopolist to stick quite close to design capacity throughout. Optimal profits drop from $81 million for $\Delta C = 100{,}000$ to $15 million for $\Delta C = 25{,}000$. Another sizable increase in EC would undoubtedly make the port an unprofitable investment for the monopolist, at least for the smaller ΔC's; that is, he would never invest in the first berth.

If one keeps EC at $\$10^7$ but increases the sample design capacities to 5 million tons per year, 2 million tons per year and 1 million tons per year respectively, then the monopolist buys one berth and his corresponding present valued profits are, in each case, slightly in excess of $106 million, and the profit maximizing price stays within 20¢ of $50/ton throughout. The reason for mentioning this particular set of parameters will become clear when we compare these results with the corresponding results for an economically efficient port in the following section.

3. Real World Income Maximization

The second objective function which we wish to investigate for the same port is economic efficiency. Assuming all prices exogenous to the port equal marginal social costs,* then the necessary conditions for maximum world income are:

1) In any short-run situation, the port must charge the marginal social cost for its service.

2) The port should expand as soon as the capital (the resources) required for the expansion is more valuably employed in the port than elsewhere.

Several authors have intimated that these two principles are contradictory when one is faced with large, indivisible capital investments. We shall see that as long as, for the <u>smallest</u> possible level of investment, the average cost curve <u>eventually</u> turns upward (as it must when the investment is operating at greater than design capacity), not only are the two principles not contradictory, they are essentially and necessarily tied together.

Analysis of the short-run situation follows directly from the marginal cost pricing principle. If at the beginning of the nth period, t_n, the port has C_n units of design capacity installed and the demand for the port's service is $D(p,t_n)$, then the economically efficient price for the period (t_n, t_{n+1}) is given by solving

---

*In the real world, the situation is considerably complicated by the cartelization of the liner trades. In this situation, a decrease in cargo-handling cost may and has been appropriated by the liner conferences, whose freight rates include cargo handling (see reference [3]). We will conveniently ignore this problem.

(3.1) $D^{-1}(x^*(C_n,t_n),t_n) = MC(x^*(C_n,t_n),C_n)$

for the economically efficient throughput, x^*. The economically efficient price, $p^*(C_n,t_n)$ is equal to $D^{-1}(x^*(C_n,t_n),t_n)$.

Application of the second principle is slightly less straightforward. We suppose a perfect capital market, and let the social cost of capital be r% per year. Let the corresponding discount rate be ρ. Then the second principle says the port should expand as soon as the present value of the earnings of the expansion, <u>where these earnings result from the above marginal cost pricing philosophy</u>, net of outlays associated with the expansion is positive when discounted at an interest rate r.

The problem is that, given the coupling between pricing and expansion implied by marginal cost pricing, the future earnings of a berth constructed now depend on the expansion alternatives followed in the future. Thus, in order to tackle the expansion problem, we must, as in Section 2, work backwards from the far distant future, figuring out what expansion alternative will be followed for every possible situation the port might get itself into.

At this point, we will make one additional assumption: each additional unit of capital investment--each additional berth, if you will--is exactly similar to the berths already in operation as far as the shipper is concerned.* Each berth performs the same service with the same marginal costs.** In

*We also now need a requirement which is the dynamic equivalent of non-decreasing long-run average costs. This will be discussed in more detail later.

**This assumption is made for the purposes of expositional convenience only, although other assumptions will lead to some computational problems (excessive memory requirements).

such a situation and once again assuming marginal costs are non-decreasing, if $x(C_n, t_n)$ is the total throughput for the port in the nth period, then common sense and symmetry suggest that efficiency requires that the throughput be divided equally among the berths. Each berth will handle $x(C_n, t_n)/(C_n/\Delta C)$ units of cargo. Also, of course, the price charged for this service will be the same at each berth during this period. Under marginal cost pricing, the operating revenues of <u>each</u> of the $(C_n/\Delta C)$ installed berths in the nth period will be

$$(3.2) \qquad r^*(C_n, t_n) = \frac{p^*(C_n, t_n)D(p^*, t_n) - VC(x, C_n)}{(C_n/\Delta C)}$$

If this is the case, we can define $W_n(C_n)$ to be the present value of the earnings net of variable costs of a berth from t_n on, if at t_n, C_n units of design capacity are installed and if from t_n we follow an economically efficient pricing and expansion policy. Thus, W_n refers to the future operations of any one of the already installed berths present valued back to t_n.

The job before us, then, is to develop a recursive method for computing $W_n(C_n)$. As in Section 2, we will start from some time in the relatively distant future, t_N, where demand is no longer growing and, therefore, no further port expansion is ordered. In this steady-state situation, we have

$$(3.3) \qquad W_N(C_N) = \frac{r^*(C_N, t_N)}{1 - \rho}$$

for $r^*(C_N, t_N)$ will be earned by each berth in each period from t_N on. This relation yields $W_N(C_N)$ for all possible values of the design capacity at t_N.

Now let's consider the situation at t_{N-1} given some installed capacity C_{N-1}. The net present value of an additional berth ordered at t_{N-1} in this situation, $V_{N-1}(C_{N-1})$ is made up of the net operating revenues this berth will earn from t_N on less the present value of the expansion costs to which the port commits itself when it orders the berth or

$$(3.4) \quad V_{N-1}(C_{N-1}) = -EC(C_{N-1}, t_{N-1}) + \rho W_N(C_{N-1} + \Delta C)$$

where $V_{N-1}(C_{N-1})$ is the net present value of the investment present valued back to the time at which it is ordered, t_{N-1}.

Following the second basic principle of efficient port pricing and expansion, the expansion should be ordered if $V_{N-1}(C_{N-1}) \geq 0$; otherwise it should not. Let $e^*(C_{N-1}, t_{N-1})$ be 1 if the efficient choice in this situation is to expand and 0 otherwise. In order to move back to t_{N-2}, we must first compute the earnings of a berth from t_{N-1} on by

$$(3.5) \quad W_{N-1}(C_{N-1}) = r^*(C_{N-1}, t_{N-1}) + \rho W_N(C_{N-1} + e^*(C_{N+1}, t_{n-1}) \cdot \Delta C)$$

Notice that the future earnings of a berth which is already installed at t_{N-1} depend on our expansion choice at t_{N-1} since this expansion will change both the throughput and price at each berth. Having computed W_{N-1}, we can compute

$$(3.6) \quad V_{N-2}(C_{N-2}) = -EC(C_{N-2}) + \rho W_{N-1}(C_{N-2} + \Delta C)$$

Once again, if $V_{N-2}(C_{N-2}) \geq 0$ then $e^*(C_{N-2},t_{N-2}) = 1$; otherwise $e^*(C_{N-2},t_{N-2}) = 0$. And

$$(3.7) \quad W_{N-2}(C_{N-2}) = r^*(C_{N-2},t_{N-2}) + \rho W_{N-2}(C_{N-2} + e^*(C_{N-2},t_{N-2}) \cdot \Delta C)$$

At this point we can move back to t_{N-3} and repeat the process.* Working our way backwards in this fashion, we can construct the entire efficient expansion table $e^*(C_n,t_n)$ for all possible combinations of C_n and t_n. We can then move forward through this table starting at the present, t_0, with the present installed capacity, C_0, picking out the economically efficient policy. Once one has the efficient expansion policy, it is an easy matter to recompute the sequence of short-run prices and corresponding throughputs using marginal cost pricing.

Notice that this pricing and expansion policy has a very interesting property. Although at any time we follow strict marginal cost pricing based on short-run capacity and short-run demand, the port as a whole over its life does not lose money. It will not require a subsidy. The periods of under-utilization--throughput less than design capacity (price less than average cost)--and congestion--throughput greater than design capacity (price greater than average cost)--work out so that the entire present-valued time stream of revenues

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*Notice that in computing the net present value of an additional pier $V_n(C_n)$, <u>it would be incorrect to subtract the loss in earnings to the already installed berths</u> due to the reduction in price and individual throughputs. This would be double counting, for when we get back to the decision to build the berths that are already installed at t_n we will--looking forward--take cognizance of the fact that the berth we are thinking about adding at t_n will reduce the earnings of the berths which we built at an earlier point in time.

just covers the entire present-valued time stream of costs. This is required if the long-run allocation is to be efficient.

In 1938, Hotelling, in the process of advocating strict marginal cost pricing, suggested that "congestion charges" might cover losses in areas where marginal costs were less than average costs [5]. This suggestion has come in for considerable criticism [6], and a good part of the literature on marginal cost pricing has dealt with marginal cost pricing's supposed requirement of subsidies [7]. However, the above analysis indicates that marginal cost pricing coupled with efficient investment not only could result in full costs being covered but _must_ so result, at least given certainty with respect to future demand growth.* _Efficiency through marginal cost pricing and full cost recovery not only are not inconsistent, they are intimately and necessarily tied together_. Some writers have been misled by the persistent overcapacity generated in many markets where marginal cost pricing is not followed. If one wishes to see how marginal cost pricing operates, one should turn to the truly competitive markets. The tanker charter market is an example: at any point in time, the spot charter rate equals marginal cost, yet the marginal independent tanker owner just covers the full cost of his investment over the life of the investment.

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*Also note that since we have assumed a single investor, we have ruled out uncertainties with respect to supply as well as demand. However, uncertainty does not vitiate the basic marginal cost pricing argument. It implies only that even if an efficient expansion policy is followed, the port may make either long-run profits (demand grows faster than expected) or long-run losses (demand grows slower than expected). This is true of any other pricing and expansion policy which treats sunk costs as sunk costs under uncertainty.

Essentially, all this algorithm does is simulate the competitive market dynamic. However, it does so in a somewhat more systematic manner than the trial and error process used by actual competitive markets. Under uncertainty -- and as long as the society is willing to act like an expected-value decisionmaker, uncertainty can be incorporated without difficulty*--neither the competitive market nor the algorithm can hope to follow a policy which given hindsight is unimprovable. However, the algorithm can avoid one sort of error which certain competitive markets are prone to and that is the phenomenon where all suppliers read the present situation as profitable and decide to expand without accounting for the impact of this total expansion on future prices. Chastened by the results, they become overly conservative. This process, combined with construction lags and growing periods, leads to a certain excess jerkiness in some markets' operation, which in turn can lead to unduly prolonged losses (profits), calls for subsidy, protection, regulation, attempts at cartelization, etc.

Nonetheless, the real utility of the algorithm is not in replacing competition in those markets where it has been

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*One must assign probabilities to the future such that the probability of each uncertain demand variable at t_{n+1} depends only on the state of things at t_n. One then replaces V_n and W_n by their expected values and proceeds exactly as before to generate the efficient expansion table. However, an additional state variable will be required for each random variable and the resulting policy will, like the actual market, be adaptive in the sense that the decision actually taken at some time t_m in the future will depend on what has happened between now and t_m. One can also handle constant risk aversion in an analogous manner. See reference [4].

maintained, but rather in substituting for competition in those markets where it has not been maintained. The above process, however jerky, generally cannot stray too far away from allocative efficiency for too long. However, in those situations where it does not pay to maintain multiple suppliers in order to keep the competitive market dynamic going or, more widely, in situations where the institutions for implementing the dynamic have not developed or have been suppressed, an artificial means of simulating this process is required. The above line of reasoning can serve as such a substitute. In short, the algorithm or its generalizations might be used to manage or regulate a variety of different public and private monopolies, natural and otherwise. The generalizations are primarily limited by the amount of computational effort one is willing to undertake. Some of them come surprisingly cheap; see, for example, Section 5, and footnote on preceding page.

Results for sample problem

A program implementing the above algorithm has been written and exercised on the sample problems of Section 2. The results displayed in Figures 3, 5 and 7 for exactly the same demand and cost structures for which the monopolist's optimal policies are shown in Figures 2, 4 and 6.

In each case, the number of berths installed and the throughput is about double the respective monopoly profit maximizer's policy. For ΔC = 100,000 (Figure 3), the port has no trouble keeping up with the early stages of demand growth and marginal costs and price is always less than $2.00, approximately 1/25 of the monopolist's optimal price. Interestingly enough, the efficient policies tend to operate at higher utilizations than the monopolist, always dropping price enough so that throughput is equal to or greater than the design capacity. To put it another way, for this demand and cost structure, the efficient port doesn't expand until (under its pricing policy) the new capacity will be fully utilized. As a result, the steady-state solution involves throughputs slightly higher than design capacity, since in order to fully utilize further expansion, price would have to be dropped below marginal cost. (The demand surface is extremely inelastic for prices of less than $5.00.) One result of this is that in Figure 3, the port ends up by making a slight profit.

In Figure 5, the port's expansion is clearly limited by the constraint that it can only expand once a year. As a result, efficient allocation of the available capacity involves prices of up to $10.00 before expansion is able to catch up. A much more severe case of this situation is shown in Figure 7, where expansion is unable to catch up until t = 35. Efficient pricing for this situation involves marginal costs of up to $39.00. As a result of the expansion constraint, the ports in Figures 5 and, especially, 7 make substantial profits. From the point of view of world income, this is a bad sign. It indicates that if we were to relax the constraint that only one berth can be constructed per year, an efficient expansion policy would take advantage of this relaxation.* However, given the constraint, the port must allocate its scarce resources efficiently. Hence the high prices.

In general, the efficient port's prices are a good deal more variable than the monopolist's, making the point that efficient allocation calls for considerably more price flexibility than the monopolist--and most port administrators--care for.

Of course, both the monopolist's and the economically efficient pricing policies involve more flexibility than typical average cost pricing, however defined. And both involve decreases in price immediately after an expansion, while average cost pricing involves either no change or an increase in price, depending on the accountant's degree of allegiance to the past.

In Figures 9, 11 and 13, we have increased FC to $10 million, creating the situations equivalent to Figures 8, 10 and 12. Under this considerably more adverse cost structure, for a ΔC of 100,000 tons, the port delays expansion until it is operating approximately 10% over design capacity. As a result, marginal cost and prices fluctuate in the neighborhood of $17. Halving the capacity, Figure 11, results in approximate doubling of the efficient marginal costs, which are now high enough to have a significant effect on throughput. That is, the economically efficient port no longer doubles the

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*This relaxation would involve no problems for the basic algorithm.

number of piers with halving of the design capacity. This phenomenon becomes even more pronounced with a further halving of design capacity in Figure 13. Despite this decrease in ΔC, the port buys no more berths than in Figure 11, although it brings them on a little sooner. As a result, marginal costs approximately double and prices begin to approach those charged by the monopolist in a similar situation. The corresponding throughput is halved. Notice that the port is still operating at little more than 10% over design capacity. The marginal cost curve at this point is very steep, so the efficient port chooses to increase price rather than try to push more throughput through these low-capacity berths. This behavior contrasts rather sharply with the typical real-life response to limited or expensive capacity.

If one maintains EC at $10 million but increases ΔC to one million tons per year, 500,000 tons per year, and 250,000 tons per year, an interesting phenomenon occurs which demonstrates a fundamental limitation on the above line of reasoning. For EC = $\$10^7$ and $\Delta C = 10^6$ tons/year, the program implementing the above algorithm chooses not to build any berths. However, when ΔC drops to 500,000 tons/year, the algorithm buys one pier and runs 37 million tons of cargo through it over the life of the port. At first glance, this would seem to imply that if our cargo handling technology becomes good enough, we don't handle any cargo. The problem is that with a ΔC of 1 million tons and the sample demand surface, it is impossible even with only one berth to get on the up side of the average cost curve even when demand has reached its full growth. If the investor invests at all, he is faced with unavoidable decreasing average costs at full demand growth. The basic condition for long-run stability of a competitive market is violated. Notice that it is not necessary that we not have decreasing average costs throughout the process. We require only that we not have decreasing average costs after full growth has been reached for the smallest possible investment. In actual fact, one would rarely run into a situation where the smallest possible investment resulted in throughputs less than design capacity at full demand growth. When one views the problem dynamically, the condition for operation of a competitive market is much weaker than some interpretations of static analyses would have us believe. Unavoidable decreasing average costs present no problem for the monopoly profit maximizer, as is indicated by the last paragraph of Section 2.

Finally, it should be obvious that indivisibilities in the cargo-handling process itself present no conceptual problems. For example, suppose, as is actually the case, that labor is available only in units of "gangs". If the size of a gang is not negligible compared to overall labor requirements, this will lead to ups and downs in the marginal cost curve as defined earlier, violating our assumptions. The solution is to regard the hiring of a gang for a period as a "fixed" investment. That is, once we find ourselves with C_n berths at time t_n, we examine all possible numbers of gangs and for each possibility obtain the resulting marginal cost. We hire as many gangs as will pay for themselves under the resulting pricing and proceed as before.

4. Maximization of Regional Income

From the point of view of the beneficiaries of the port's operations, the first two objective functions we have examined can be regarded as extreme cases. In the profit maximization case, we were only interested in maximizing the wealth of the port's owner or controller. The economically efficient policy regarded the world as the group whose total income was to be maximized. In reality, a port may very likely choose to function in such a manner as to maximize the real income of some intermediate subset of the world's people. The Port of Singapore may wish to operate in such a manner as to maximize the income of the people of the Republic of Singapore. Such an objective function requires that we combine "optimal" tariff theory with the foregoing analysis. We will consider the two-good case: one import, m, and one export, e, and make the following assumptions.

1) Competition everywhere but in port prices;

2) No other tariff policy;

3) No externalities;

4) No retaliation by rest of world;

5) Both goods produced domestically.

Let $\bar{}_e (\bar{}_m)$ denote the foreign price of the export (import) in some time period; let $p_e (p_m)$ denote the domestic price of the export (import); and let $a_e (a_m)$ denote the price the port charges for handling a unit of export (import) in this time period.

Assuming no transport costs other than the port system and that the demand for exports (imports) depends only on the foreign (domestic) price of the good, at any time t_n, with installed capacity C_n, the following short-run relations exist:

(4.1, 4.2) $\pi_e = p_e + a_e \qquad p_m = \pi_m + a_m$

(4.3, 4.4) $x_e = d_e(\pi_e) \qquad x_m = d_m(p_m)$

(4.5, 4.6) $x_e = s_e(p_e) \qquad x_m = s_m(\pi_m)$

where d_e and d_m (s_e and s_m) are the momentary demand (supply) for the goods in the market (producer) country. To maximize regional income, a necessary condition which must be satisfied is that the domestic price of the export (import) must equal the marginal revenue (cost) of that good after cargo handling charges. We have:

(4.7) $$MR(x_e) = \pi_e + \frac{\partial \pi_e}{\partial x_e} x_e - \frac{\partial \pi_m}{\partial x_e} x_m - \frac{\partial}{\partial x_e} VC(x_m, x_e, C_n) = p_e$$

(4.8) $$MC(x_m) = \pi_m - \frac{\partial \pi_e}{\partial x_m} x_e + \frac{\partial \pi_m}{\partial x_m} x_m + \frac{\partial}{\partial x_m} VC(x_m, x_e, C_n) = p_m$$

From (4.1), (4.2), (4.7) and (4.8) we have:

(4.9) $$a_e = \frac{\partial}{\partial x_e} VC(x_m, x_e, C_n) - \frac{\partial \pi_e}{\partial x_e} x_e + \frac{\partial \pi_m}{\partial x_e} x_m$$

(4.10) $$a_m = \frac{\partial}{\partial x_m} VC(x_m, x_e, C_n) - \frac{\partial \pi_e}{\partial x_m} x_e + \frac{\partial \pi_m}{\partial x_e} x_m$$

In words, the marginal regional cost of handling one extra unit of export, say, is the resource cost of handling the unit plus the loss of revenue resulting from any associated decrease in export price and the loss of income resulting from any associated increase in import price.

Given the proper conditions on the underlying demand, supply and cost functions, the set of equations (4.1) through (4.8) can be solved for the regional income maximizing value of throughput, port charge, domestic and foreign price for any short-run situation (t_n, C_n). This is the regional income maximizing counterpart of short-run price equalling marginal cost for the world income maximizing program. Thus, it must be repeated for each combination of possible expansion time and installed capacity. With this in hand, we can apply the same dynamic programming-like reasoning and logic as in the economically efficient policy, with expansion taking place as soon as the stream of revenues has a present value greater than expansion cost. The argument generalizes in a straightforward manner to the M import N. Conceptually, then, the objective of maximum regional income presents no new theoretical problems. However, even in the one import - one export case, repeatedly solving an 8 x 8 set of non-linear equations presents some obvious numerical problems and we as yet have not attempted it. In many practical cases, it may not be necessary. For example, if the Suez Canal Authority wishes to price and expand the Canal in such a way as to maximize the income of the people of Egypt, it is quite likely they should follow something very close to the monopolist's optimal policy. This will result in certain inefficiencies, decreases in world income; however, most of this loss will fall outside Egypt.

On the other hand, for developing countries' ports trading with developed countries in the typical situation of inelastic demand for imports and inelastic supply of exports, it is likely that the national income maximizing port pricing and expansion policy should be something close to the economically efficient policy, since most of the loss of world income associated with an inefficient policy will fall on the developing country.* Also, the more elastic the demand for the port's services, the closer the monopolist's and the efficient policy will become. Thus, for highly elastic demands, there will be little difference between the two.

Unfortunately, there will be some truly intermediate cases where the computational travail may be worth the effort.

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*In the real world, this suggestion may not be true for general cargo shipments due to the cartelization of the liner trades.

5. The Multi-Commodity Port

As hinted in the last section, exactly the same line of reasoning for all three objective functions can be applied to the multi-commodity port. In fact, for the private profit and world income objectives, surprisingly few computational difficulties are encountered.

Consider the same port as before, except that now it is handling a number, M, of different commodities. Let x_i and p_i be the throughput and price charged on commodity i in some period. Let $X = \{x_1, x_2, \ldots x_M\}$ and $P = \{p_1, p_2, \ldots p_M\}$. In general, the demand of the ith good, $D_i(P,t)$, will depend on all the short-run prices and time, and the variable cargo-handling costs will depend on all the throughputs and the installed capacity, $VC(X, C_n)$. We assume $\partial D_i/\partial p_i < 0$ and $\partial VC/\partial x_i \geq 0$.

For the private profit maximizer, at any decision point t_n given C_n the requirement that marginal revenue equals marginal cost leads to the standard set of equations:

$$(5.1) \qquad \frac{\partial}{\partial x_i} (D_i^{-1}(X, t_n) \cdot x_i) = \frac{\partial VC}{\partial x_i} (X, C_n) \qquad i = 1,2,\ldots M$$

which can at least conceptually be solved for the short-run profit maximizing throughputs $X^*(C_n, t_n)$ and prices $P^*(C_n, t_n)$ and from this point on the dynamic program looks exactly like that in the one-commodity case.

$$(5.2) \quad V_n(C_n) = \max \begin{cases} R^*(C_n, t_n) + \rho V_{n+1}(C_n) \\ R^*(C_n, t_n) - EC(C_n) + \rho V_{n+1}(C_n + \Delta C) \end{cases}$$

where $R^*(C_n, t_n) = P^*X^* - VC(X^*, C_n)$ with essentially the same boundary condition.

For the economically efficient port, the short-run throughputs and prices for t_n and C_n are given by the solution of

(5.3) $$D_i^{-1}(X, t_n) = \frac{\partial VC}{\partial x_i}(X; C_n) \qquad i = 1, 2, \ldots M$$

after which the algorithm is exactly the same as in the one-good situation. The maximum regional income case also generalizes in a straightforward manner.

The only point of this rather uninteresting drill is that there is no more need to "allocate" "joint costs" across commodities or services than there is to allocate "fixed costs" across the same service performed at different times. The "joint cost problem" disappears as soon as one makes one's objective function and options <u>through</u> <u>time</u> explicit. It is interesting to note that the fact that we have assumed that the capital investment is completely "joint" simplifies rather than complicates the dynamic program from a computational point of view. For example, if there were M types of berth, one for each type of cargo, but either variable costs or demand were interrelated, then the dynamic program would require M state variables and the size of the state space would increase combinatorially.

6. Comparison of Private Profit Maximizing and Economically Efficient Policies With Simulated "Average Cost" Pricing Policies From the Point of View of World Income

It is of interest to compare some of the pricing and expansion policies generated earlier with examples of the types of policy which ports (and other public and semi-public monopolies) try to follow. We will restrict our attention to the single-commodity port.

If you ask, as we have, a real-world port manager what his pricing and expansion policy is, a typical reply, freely translated, is "For any particular service, charge our accountant's estimation of the 'fully allocated cost' of that service. Undertake any investment which will pay for itself under this pricing policy." Perhaps the most basic problem with this definition is that in situations where the port has some monopoly power it is not unique. If a facility is experiencing high throughput, the accountant's average costs (which do not include the revenues forgone which the ships would have been willing to pay to avoid delays) will be low, prices will be low, and expansion delayed. However, if the same facility under the same demand curve is experiencing low throughput due to a high price, average costs will be high, hence, according to the above policy, prices will remain high, and either throughput decreased further or expansion brought on quickly, depending on the shape of the demand curve. In actual fact, most ports recognize that there is something anomalous about charging price for an underutilized facility and a low price for a congested one. Thus, they often depart from their stated philosophy, and with good reason.

Unfortunately, in order to simulate "typical" policies, the computer requires a complete and unambiguous definition of what that policy is. In an attempt to cover a range of possibilities, we have simulated four different policies:

1) The port sets an arbitrary initial price in year 1; this initial price was varied parametrically. In any year, if annual net income is positive, the port orders an additional berth. If the annual net income is negative, the port increases its price by 50¢ per ton. (Throughout this section, net income, average cost, and annual cost are computed in accountant fashion.)

2) The port sets an arbitrary initial price in year 1. On the basis of the resulting throughput, the port computes average annual costs. If annual income is positive and throughput exceeds design capacity by 10% or more, the port orders an expansion and sets price equal to last year's average annual cost. If annual costs exceed revenues by 10% or more, the port increases prices by 50¢ per ton without expansion. Otherwise, no investment and no change in price.

3) In any situation, the port sets prices so that quantity attracted times price equals variable costs plus an annual capital charge. Port expands if and only if the throughput obtained in this manner is greater than the presently installed design capacity.

4) Same pricing policy as in (3). Port expands if and only if throughput is greater than present design capacity by one berth capacity.

All four of these policies were exercised on the six-sample demand and cost structures used in Sections 2 and 3. Policy (1) proved extremely unstable, as might be expected. If the initial price is set below a certain amount, the port always loses money and never expands, even when throughput greatly exceeds design capacity. If the initial price is set somewhat above the same amount, the port expands very rapidly, generating persistent large excess capacity. The range of initial prices which lead to stable behavior is quite small.

Policy (2) is a trial-and-error attempt to overcome the instabilities inherent in (1). Once again, however, if the initial price is set too low, the port never expands. However, if the price is initially set in the vicinity of marginal costs or somewhat above, the resulting expansion patterns are quite similar to those generated by the economically efficient policies, although prices were slightly higher.

Policies (1) and (2) do not require that the port know the demand surface it faces; however, they do require an arbitrary choice of the initial price, which, as we have seen, can be critical. In an attempt to overcome this problem, Policies (3) and (4) assume that the port does know its present demand curve, and at any period sets price such that the resulting throughput just covers that period's annual costs, calculated accounting style. This involves an iterative solution of a highly non-linear equation, assumes that a real solution of this equation exists (not always the case) and in general is a rather more sophisticated average cost pricing policy than ports actually use. Interestingly enough, for most of our sample problems, both Policies (3) and (4) generated expansion patterns quite similar to the efficient policy, Policy (3) expanding slightly more slowly than the economically efficient policy, Policy (4) slightly faster. The final steady-state situations were quite similar both as to price and to total installed capacity, although the pricing policy in the early stages of expansion was considerably different in form, but not in general level. Frankly, we found this general similarity quite surprising. On reflection, it follows from the fact that, aside from the initial period or two, the efficient policy involves maintaining throughput quite close to design capacity where marginal costs are close to average costs. In this situation, the loss associated with this sophisticated form of average cost pricing should not be expected to be large if the policy results in approximately the same level of investment as these policies did in almost all sample cases studied.

In an attempt to obtain a little more insight into the behavior of these policies, partial equilibrium analysis was employed. The present valued sum of the consumer's and producer's surplus for each of the policies in each of the six cases was computed. These were then compared to this sum for the efficient policies. Some of the results are shown in Table 1. In general, the loss in world income associated with the monopoly profit maximizing policy is considerably greater than that associated with Policies (3) and (4), which perhaps speaks to the issue of regulated versus unregulated monopolies. As indicated above, the loss associated with Policy (2) depends critically on the choice of initial policy.

It's a little difficult to say what can be made of such a small sample of results. But on the basis of the above, it does appear possible to construct "common sense" policies which approach the efficient policy in terms of world income, at least, for one employs the rather smooth demand and cost structures we have assumed. However, it's a chancy business, depending critically on which definition of "common sense" is employed. It also appears we have done a very poor job of simulating actual port policies. Most present container ports operate at 20% or less of actual practical capacity (reference [8]). Such policies involve either subsidy or taking explicit advantage of monopoly power, which none of the above average cost policies do.

Expansion Cost = 1×10^6 Dollars

Policy	ΔC = 100,000		ΔC = 50,000		ΔC = 25,000	
	PV Surplus	Δ Surplus	PV Surplus	Δ Surplus	PV Surplus	Δ Surplus
Pareto-optimal	224.1		215.8		185.5	
Profit max.	168.3	-55.8	165.0	-52.8	149.1	-36.4
#3	220.8	- 3.3	211.2	- 4.6	180.0	- 5.5
#4	221.3	- 2.7	213.6	- 2.1	180.0	- 5.5
#2 (1.75*)	148.2	-75.8				
#2 (1.85)	223.2	- .8				
#2 (2.00)	223.1	- .9				
#2 (2.50)	223.1	- .9				

Expansion Cost = 10×10^6 Dollars

Policy	ΔC = 100,000		ΔC = 50,000		ΔC = 25,000	
	PV Surplus	Δ Surplus	PV Surplus	Δ Surplus	PV Surplus	Δ Surplus
Pareto-optimal	171.4		115.1	38.4	38.4	
Profit max.	131.0	-40.4	89.0	-26.1	31.6	- 6.8
#3	158.0	-13.5	101.3	-13.8	2.3	-36.1
#4	163.9	- 7.5	110.8	- 3.3	34.4	- 4.0

* Number in parentheses is the initial price used.

Table 1

Differences in World Income

(Millions of Dollars)

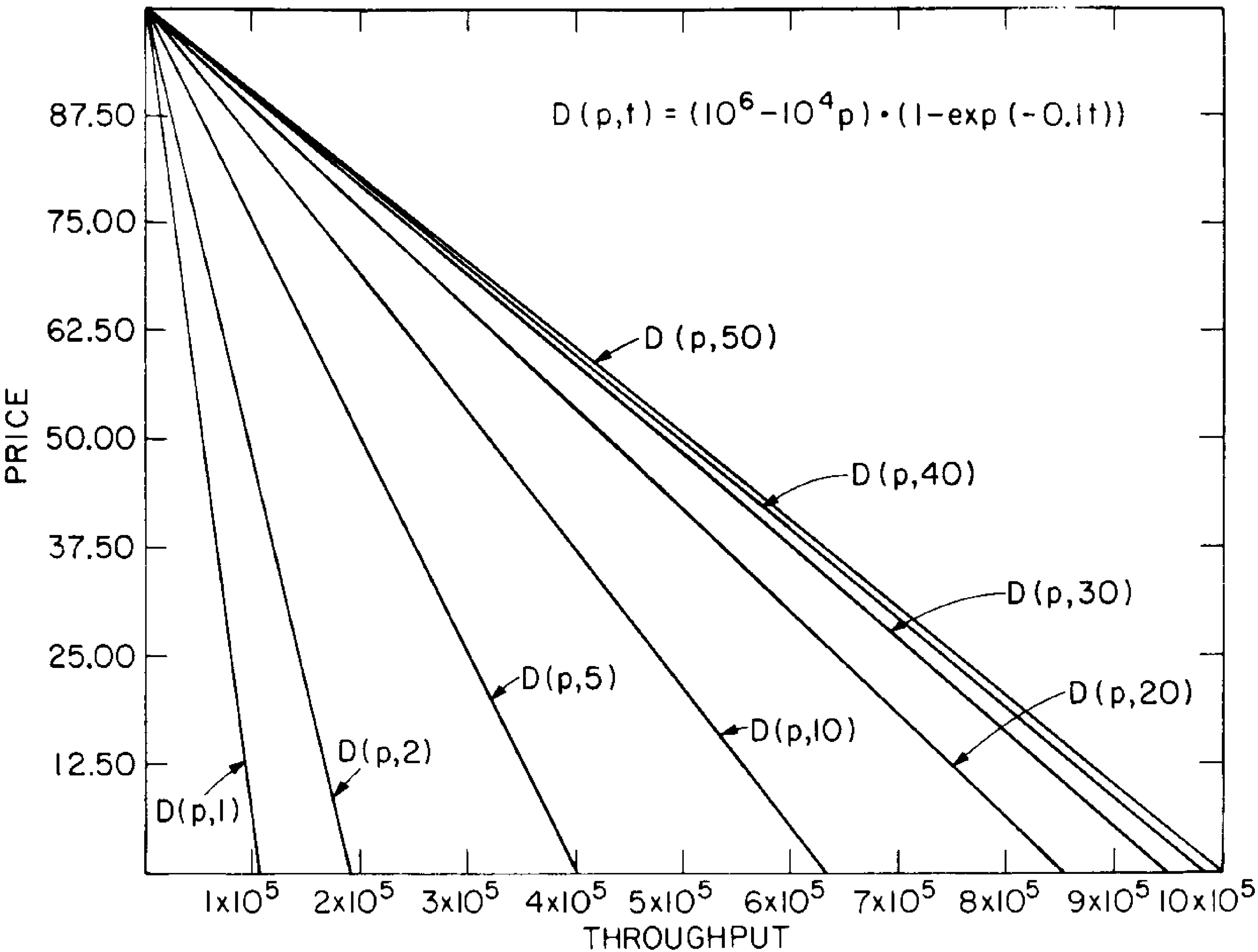

FIGURE 1. HYPOTHESIZED DEMAND SURFACE FOR SAMPLE PROBLEMS

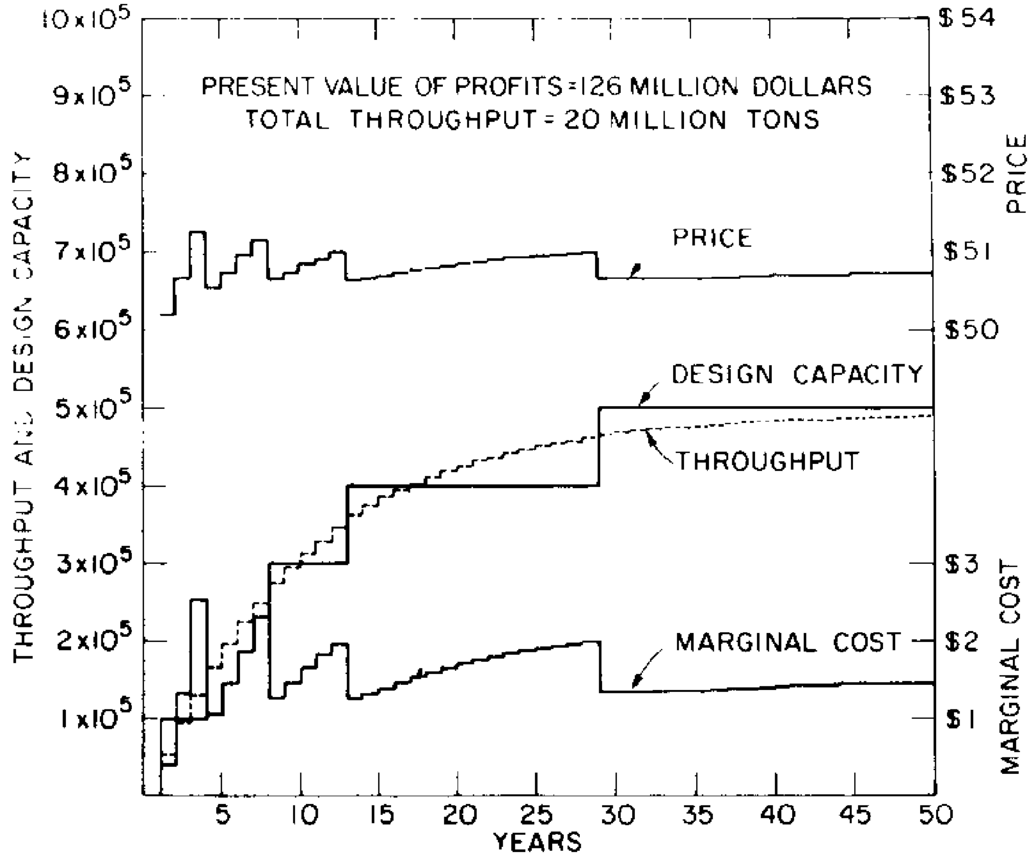

FIGURE 2. MONOPOLY PROFIT MAXIMIZING POLICY
$\Delta C = 100{,}000 \quad EC = \$10^6$

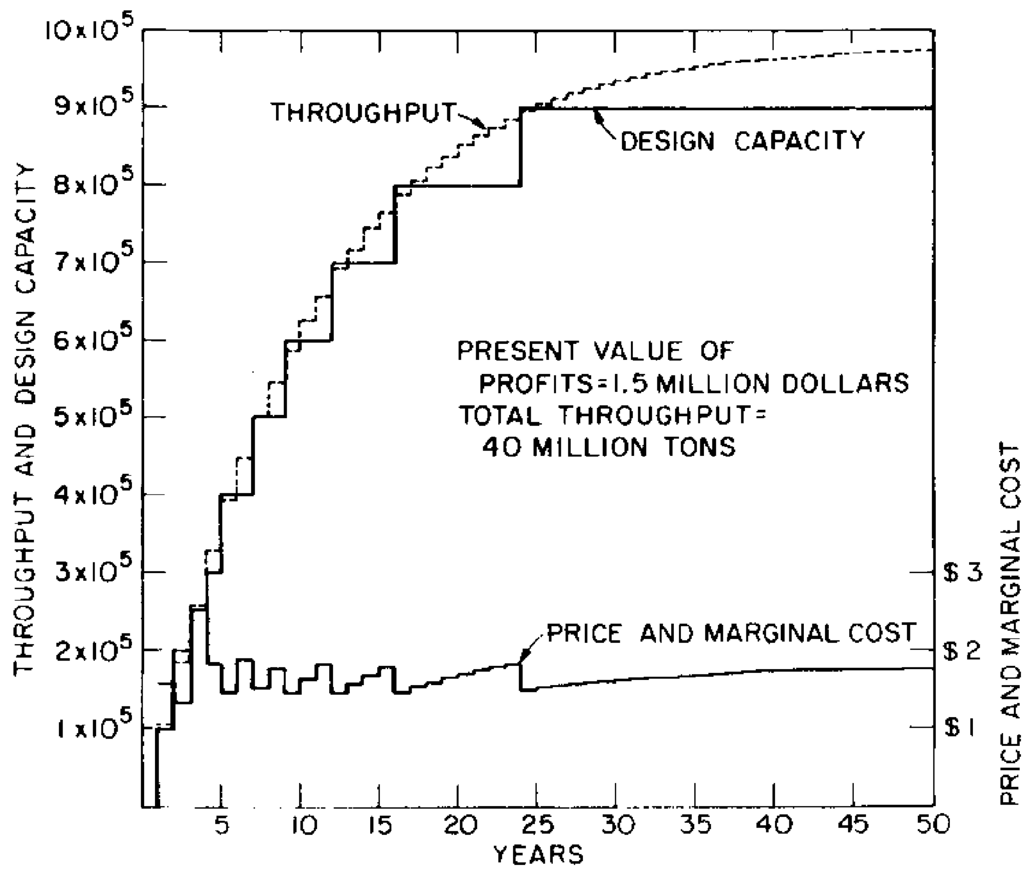

FIGURE 3. WORLD REAL INCOME MAXIMIZING POLICY
$\Delta C = 100{,}000 \quad EC = \$10^7$

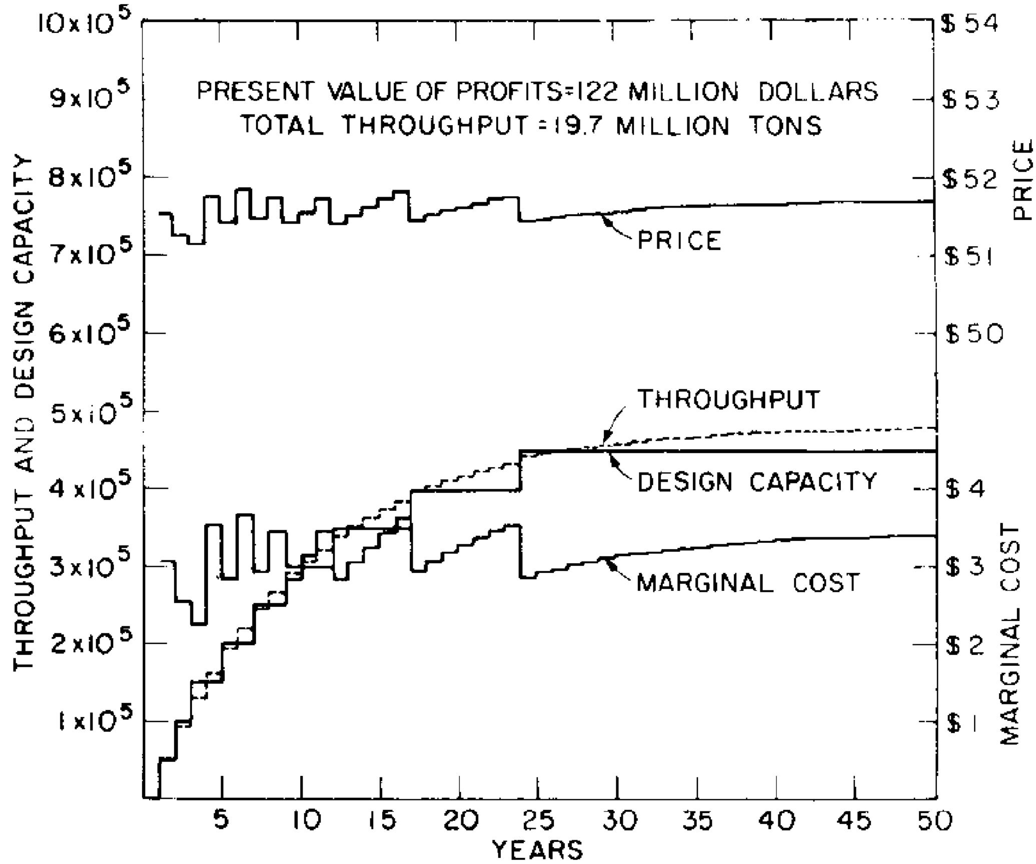

FIGURE 4. MONOPOLY PROFIT MAXIMIZING POLICY
$\Delta C = 50{,}000 \quad EC = \$\,10^6$

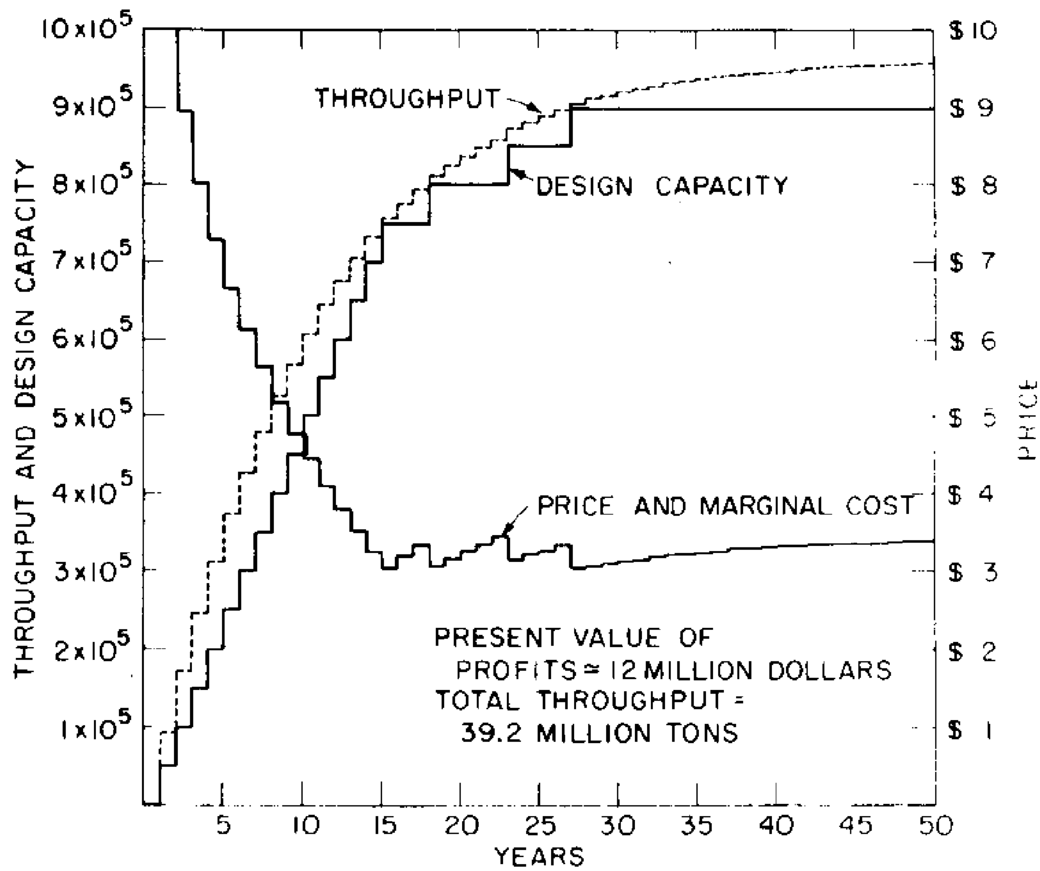

FIGURE 5. WORLD REAL INCOME MAXIMIZING POLICY
$\Delta C = 50{,}000 \quad EC = \$\,10^6$

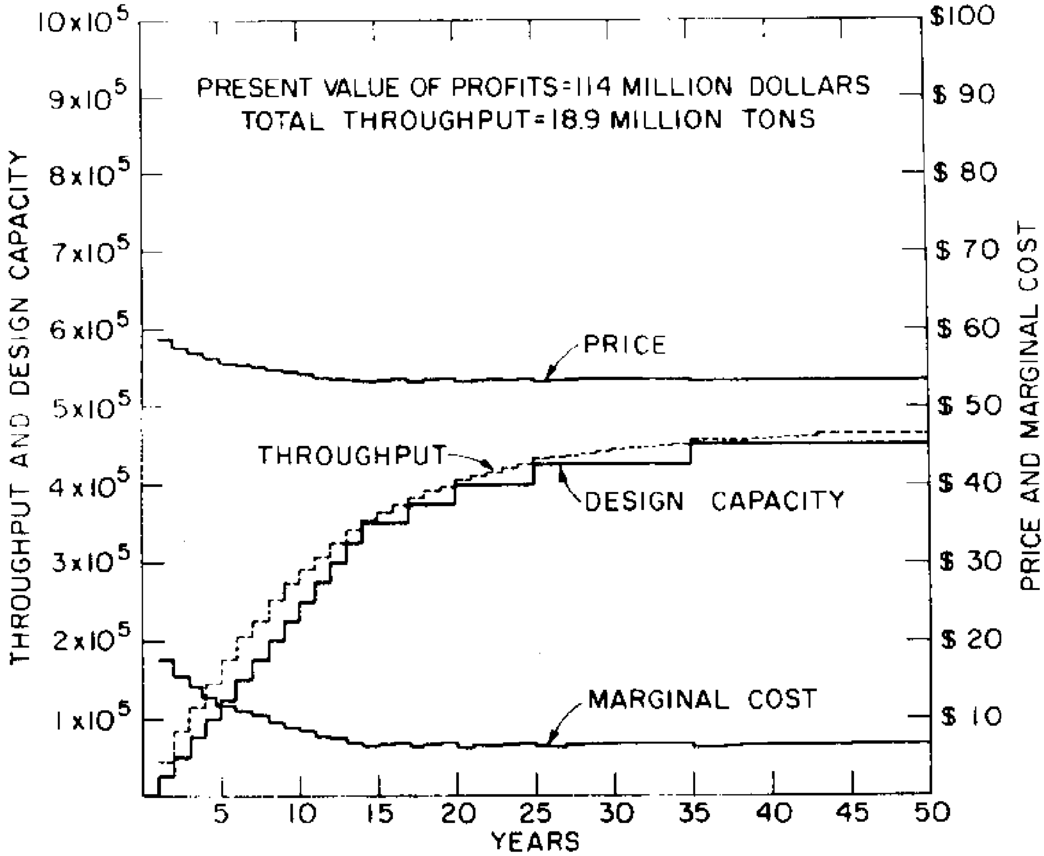

FIGURE 6. MONOPOLY PROFIT MAXIMIZING POLICY
$\Delta C = 25{,}000 \quad EC = \$\,10^6$

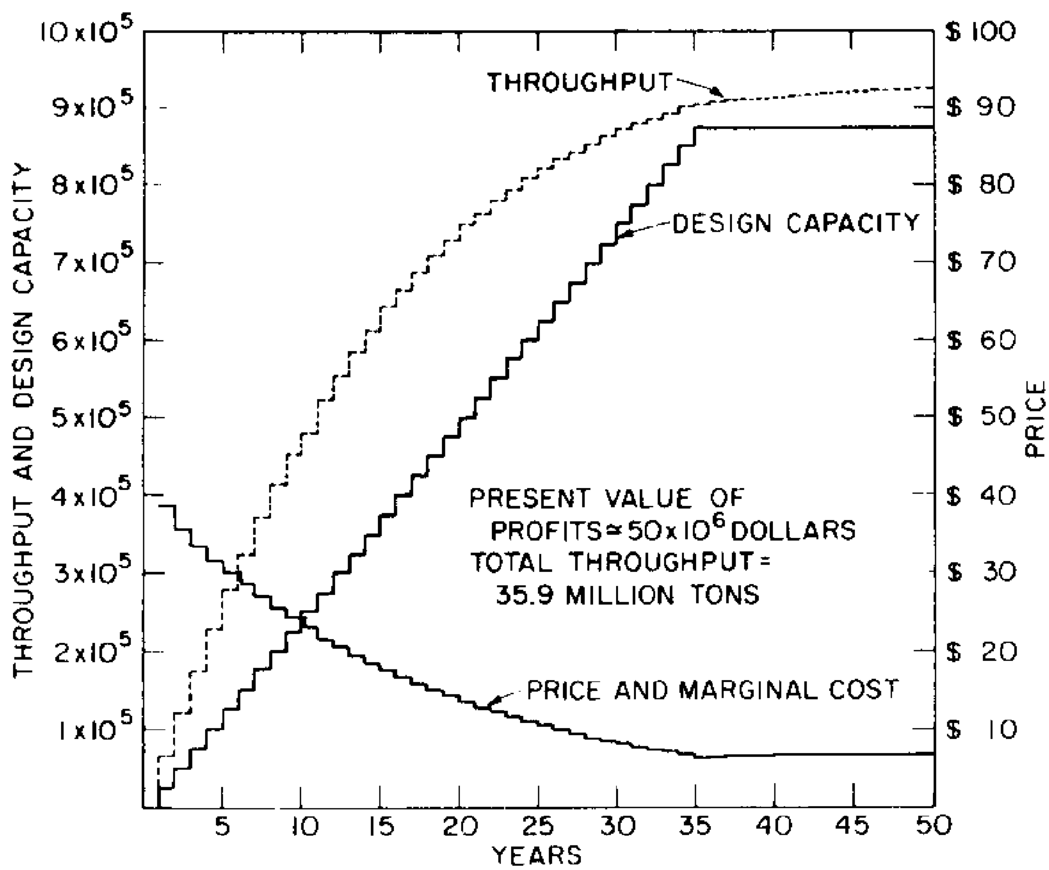

FIGURE 7. WORLD REAL INCOME MAXIMIZING POLICY
$\Delta C = 25{,}000 \quad EC = \$\,10^6$

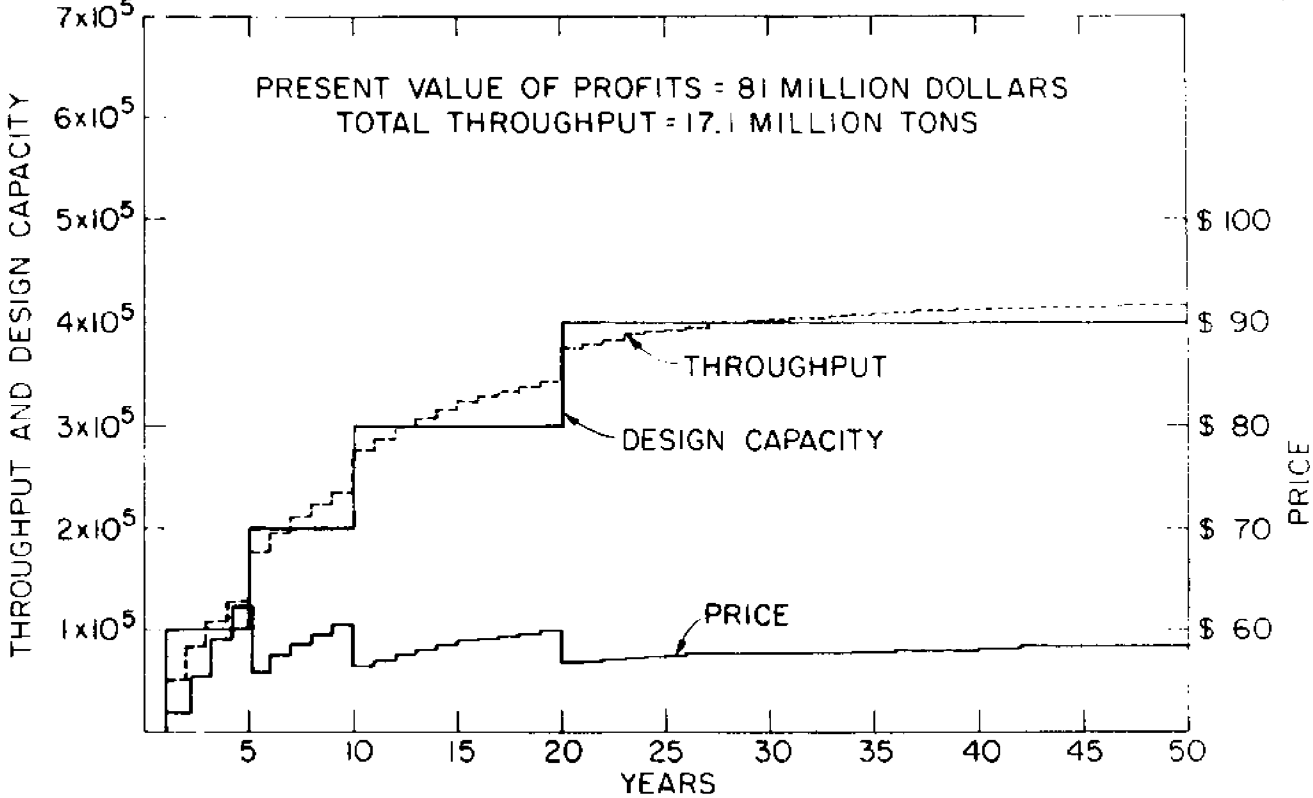

FIGURE 8. MONOPOLY PROFIT MAXIMIZING POLICY
EC = $ 10,000,000 ΔC = 100,000 TONS/YEAR

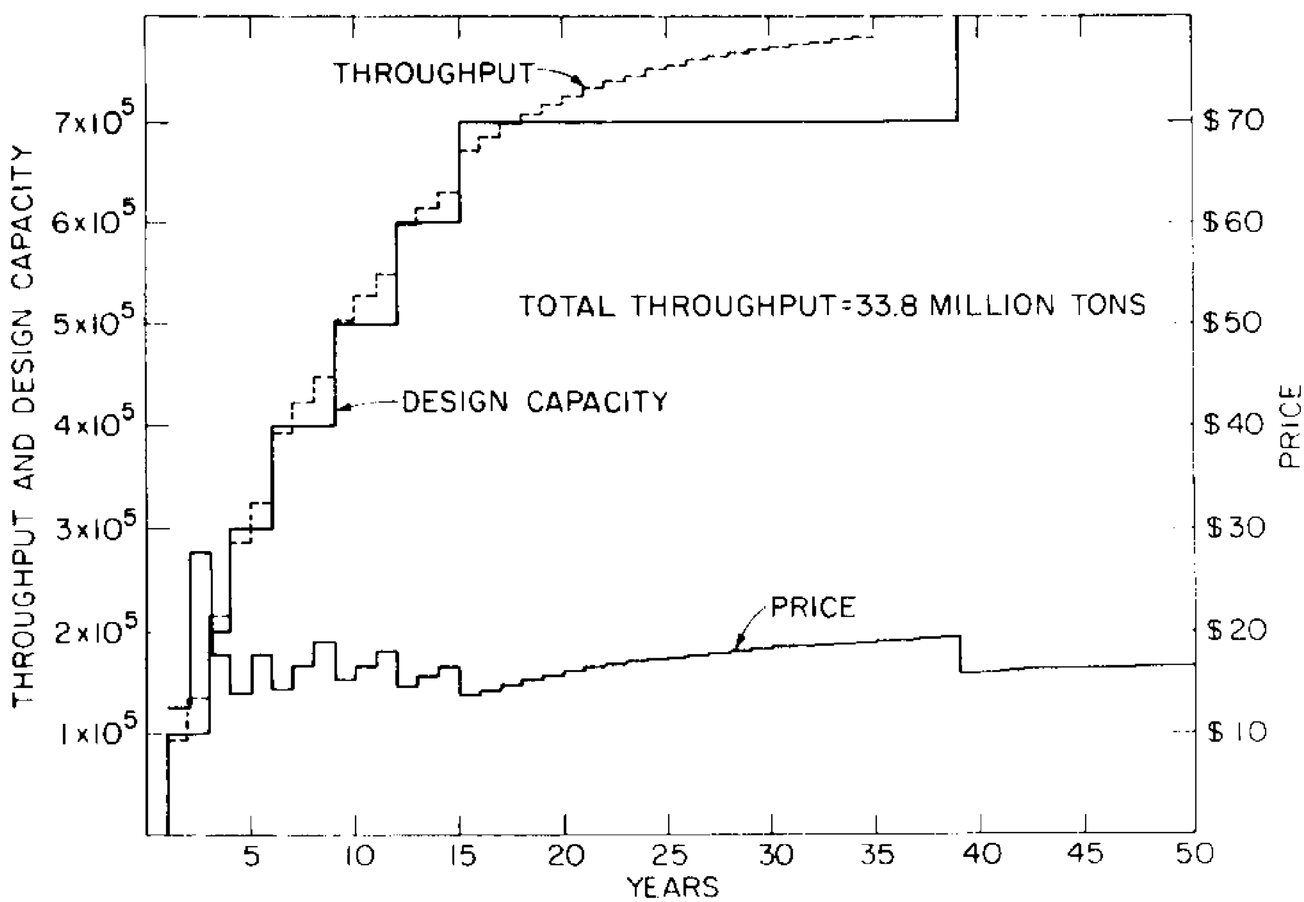

FIGURE 9. ECONOMICALLY EFFICIENT POLICY
FC = $ 10,000,000 ΔC = 100,000 TONS/YEAR

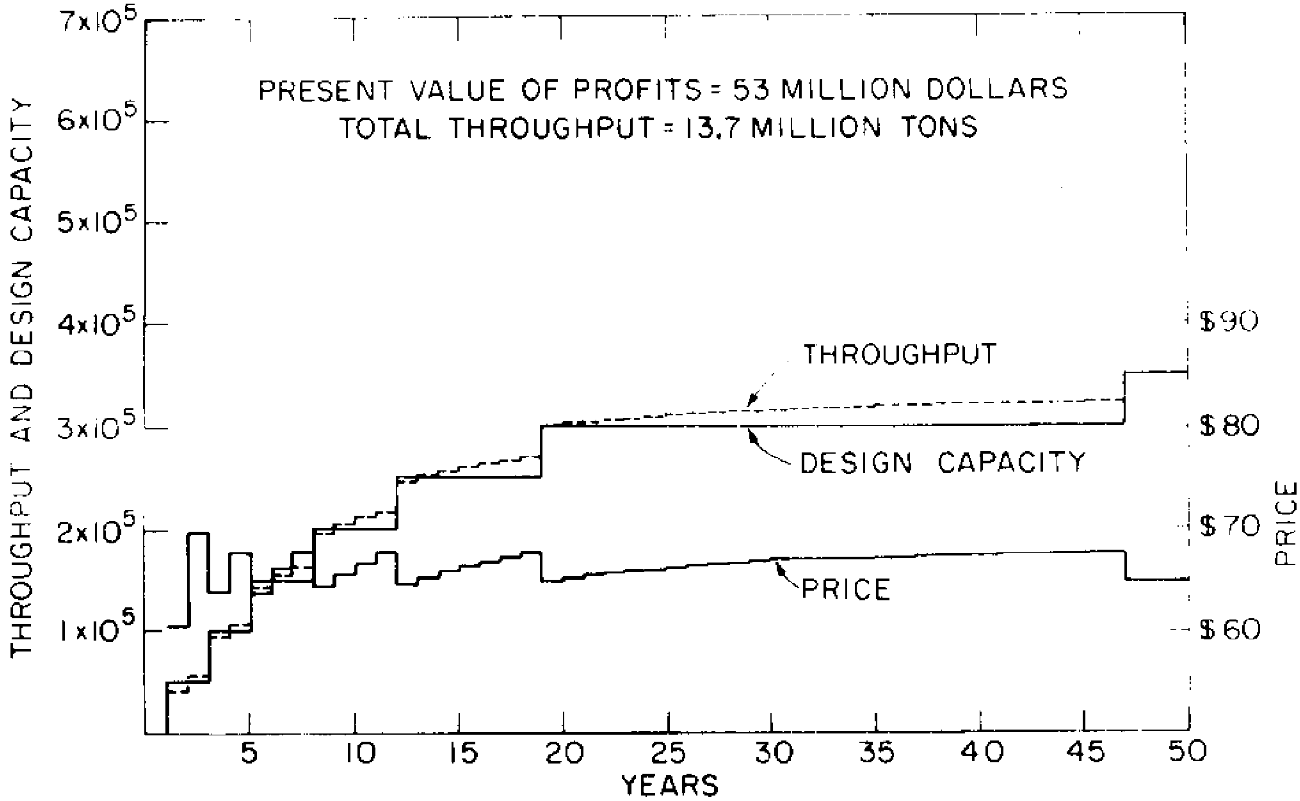

FIGURE 10. MONOPOLY PROFIT MAXIMIZING POLICY
EC = $ 10,000,000 ΔC = 50,000 TONS/YEAR

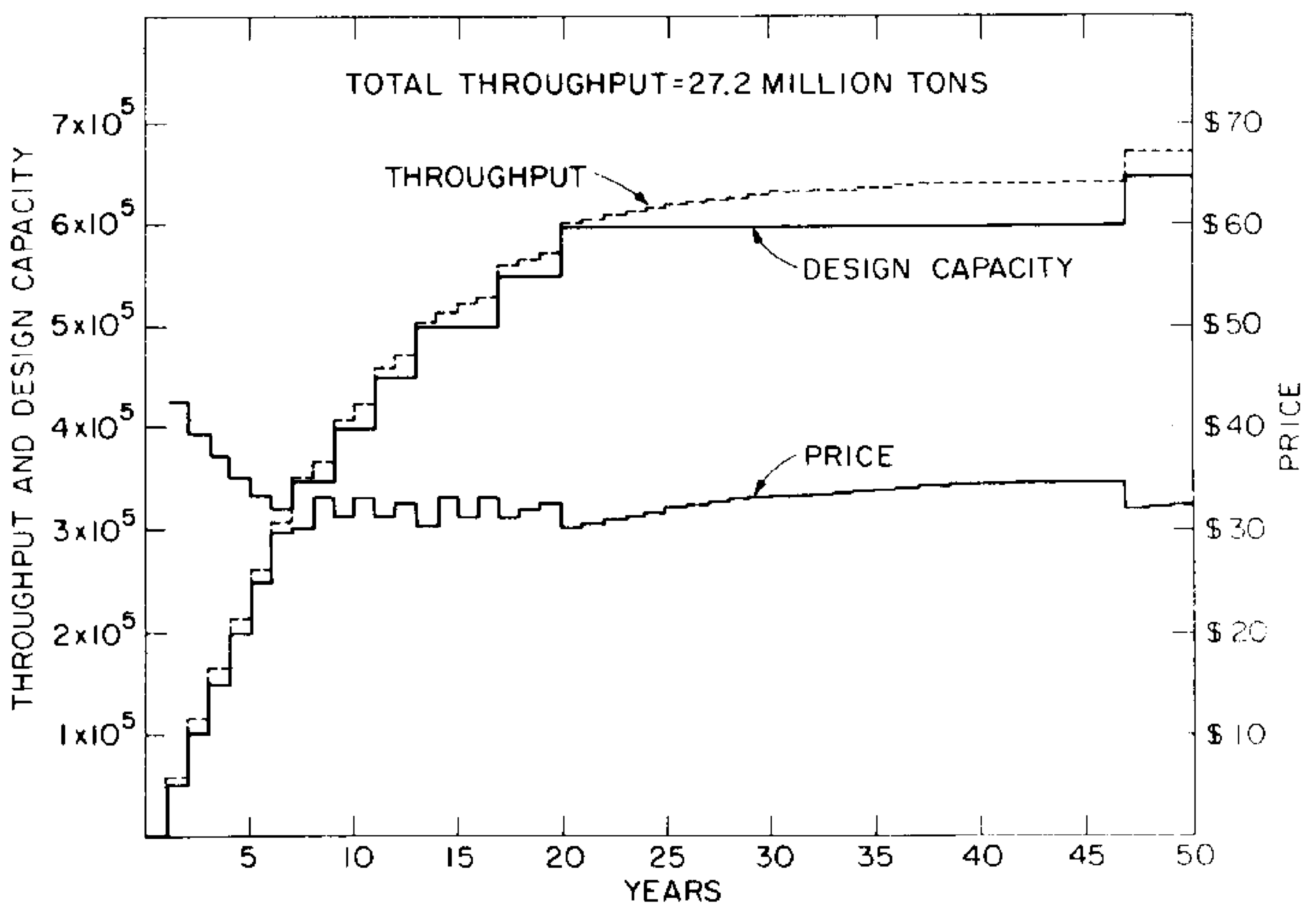

FIGURE 11. ECONOMICALLY EFFICIENT POLICY
EC = $ 10,000,000 ΔC = 50,000 TONS / YEAR

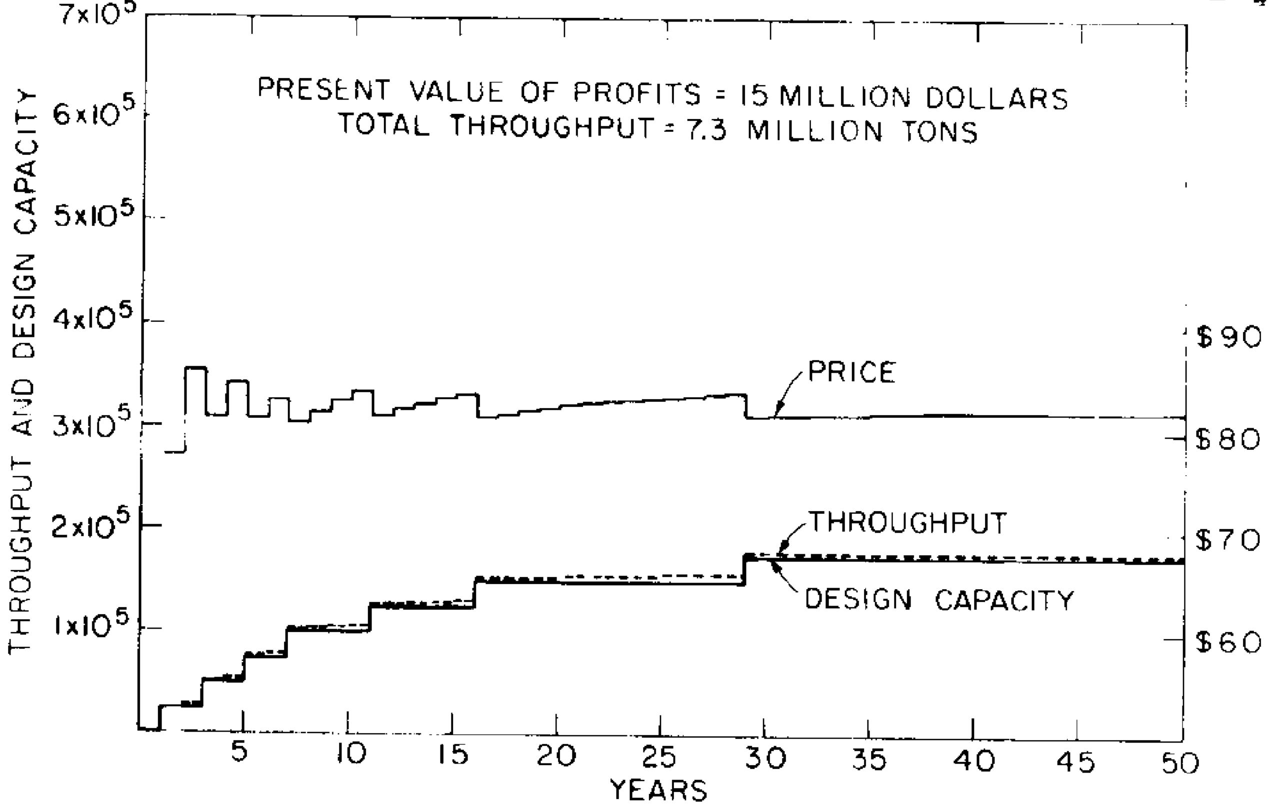

FIGURE 12. MONOPOLY PROFIT MAXIMIZING POLICY
EC = $10,000,000 ΔC = 25,000 TONS/YEAR

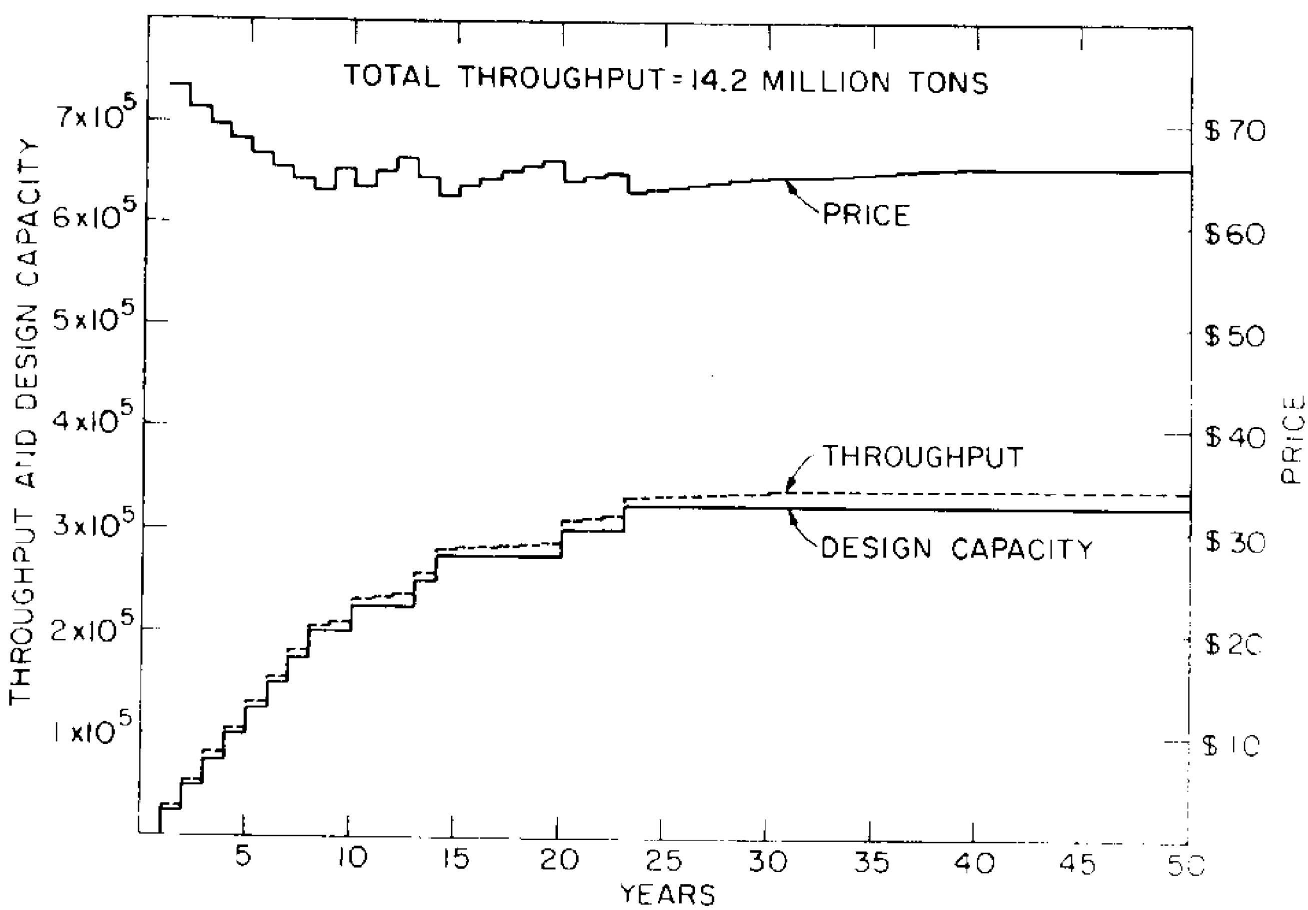

FIGURE 13. ECONOMICALLY EFFICIENT POLICY
EC = $10,000,000 ΔC = 25,000 TONS/YEAR

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