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A COMPUTER MODEL FOR PRELIMINARY DESIGN
AND ECONOMICS OF CONTAINER SHIPS

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Submitted as a Thesis for the degree of
Doctor of Philosophy

Department of Naval Architecture
and Ocean Engineering

University of Glasgow
July 1982
BEST COPY AVAILABLE

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Acknowledgements

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This thesis is dedicated to

MY PARENTS

Author's statement: All the material in this thesis is original except where reference is made to other sources.
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1. SUMMARY

This thesis is concerned with the development of a computer algorithm for determining the principal dimensions of a container ship at the preliminary design stage. The algorithm was devised to aid a Naval Architect to design the most economical ship, given the ship owner's requirements. The emphasis has been on developing an algorithm which acts as an aid in the design process.

There are basically four models of the computer aided ship design which can be used in stages. The first model or algorithm is based on a deterministic approach with parametric variation of principal dimensions to locate the optimum design with minimum required freight rate. The second model incorporates optimisation techniques to arrive at the optimum ship. Though the optimisation technique is very powerful in the search of an optimum both in computer time and computing cost, the parametric method is preferred where a designer has little faith in the optimisation process or as an aid to check the answer arrived at in the optimisation process. The third model of the computer aided design can be used once the optimum has been found. A new approach to carry out sensitivity analysis is introduced. This approach overcomes the deficiencies of the past approach, in the sense that sensitivity analysis is carried out for achievable variation in variables rather than an arbitrary variation. The third model of computer aided design may be used once the designer has identified the variables, the variation of which, influences the required freight rate most. The use of the third model of the ship design may be adequate in identifying the total risk of the project. Together with sensitivity analysis, the designer can evaluate the total risk involved in an investment since the third model also incorporates a simple approach to risk analysis. However three estimates are required in the third model compared to single estimates of variables in the first and the second model. The fourth model incorporates the risk analysis by Monte Carlo method of simulation. In this model the designer can assess the
total risk of the project by generating the risk profile of the Required Freight Rate. The designer must either subjectively or objectively input the probability distribution of each of the influencing variables before using the fourth model.

The four computer aided design models form a complete suite of computer programs, which can either be used in a deterministic mode, (first and second model), or in a probabilistic mode, (third and fourth model). Compared to previous ship design algorithms developed solely to deal with deterministic phase, this thesis incorporates ideas on how to incorporate uncertainty and assess risk in capital investment in a shipping venture.

The designer can either use these computer models in stages, from deterministic phase to probabilistic phase or the models can be used on their own.
2. **AIMS OF THE PROJECT**

The main aims of the project are:—

1. To develop a computer aided ship design model which could be used at the preliminary design stage for fully cellular container ships together with the desirable feature of stages whereby different levels of sophistication may be attained to suit the needs of the user.

2. The computer model must be flexible enough to incorporate changes in the empirical data and design relationships, and must be modular in nature so that many of the algorithms can be used on their own for various other applications. It should have a user interface which would allow a variety of users e.g. Transport Economists, shipowners, Route planners, Port Authorities and Naval Architects to use it.

3. The computer model must be able to incorporate uncertainty and must include an extension to the deterministic approach, which would enable a user to choose not only the best design but also one that is less risky.

4. To show the use of this computer model as an aid to decision making at various stages of preliminary design.
This thesis, as the title suggests, is about the choice of principal dimensions of container ships at the preliminary design stage, taking into account both the technical as well as economic aspects of ship design and operation.

The work is mainly concerned with developing a computer algorithm which will enable a naval architect at the preliminary design stage to choose the main particulars, given the owner's requirement of speed, trade route characteristics and the number of containers to be carried.

The research work is basically divided into two major divisions, a deterministic approach to ship design and a probabilistic approach to ship design. The former was the framework for developing the probabilistic approach.

In spite of the fact that during the past 20 years so many preliminary ship design algorithms have been written, it is rare that they have been applied, except perhaps during a few years after their appearance in periodicals and journals. This is primarily due to the fact that cost data, on which they were based were difficult to update or the technical data were invalidated, due to advances in ship design and production methods. The algorithm presented in this thesis has been sufficiently elaborated so that the designer can tailor the weight, cost and design relationships to his own needs. Moreover the cost data can readily be updated without recourse to an extensive cost data bank.

All the algorithms have been extensively tested and validated with existing containership data and checked by carrying out step-by-step hand calculation. The primary aim was to output reasonable results.

One way of generating large numbers of alternative ship design is by parametrically varying the main variables; such as length, breadth, depth, draft and block coefficient. The optimum design is then chosen according to some chosen economic measure of merit such as Required Freight Rate.

An attempt was made to automate the procedure of selection of the optimum design. This entails applying non-linear programming algorithm or optimisation algorithm.
Many authors in the past have successfully applied such algorithms to ship design problems (1). However it was found that availability of well tested optimisation algorithms for solving problems with non-linear objective function and non-linear as well as linear equality and inequality constraints was less satisfactory. The direct search method of optimisation by either Hooke & Jeeves (2) or Nelder & Mead (3) utilising the external penalty technique was adopted.

Lastly if one is designing a ship, many of the dependent and independent variables cannot be accurately estimated. Particularly costs in the future cannot be predicted accurately. This does not mean that one cannot deal with the future, but one cannot easily predict it. However methods exist which allows one to objectively assess the risks involved in various projects in face of uncertainty. Such a method is the Monte-Carlo technique (4). An application of such an approach is shown in this thesis. The probabilistic approach forms an extension of the deterministic approach.

The project develops and uses a computer algorithm which allows the user to select the design most appropriate to his requirements, bearing in mind that the data base used for validation is of limited extent.

A sensitivity analysis is always a useful first step in evaluating the risks inherent in a shipping venture. It involves first calculating the Required Freight Rate (RFR) based on the "most likely" (or best) estimates of the variables like costs, weights etc., and then observing the effect on the RFR of changes in each of these most likely estimates. Sensitivity analysis is usually carried out for ±10% variation in variables without taking into account that for many of the variables a 10% change is not achievable in real life. In this thesis a new concept of sensitivity analysis is introduced. It however involves making three estimates instead of one for each of the variables, the "optimistic" estimate, the "pessimistic" estimate and the "most likely" estimate. The new method (4) therefore takes into account the achievable variation in the variables and its influence on RFR. It is also shown in this thesis how an investment's risk can be calculated by this new method of sensitivity analysis.
After the designer has identified the total risk of the project, and identified the variables which are most likely to affect the RFR, the sensitivity analysis might be adequate. However the next step can be the production of a risk profile of RFR. "Pessimistic" and "optimistic" estimates provide an indication of the uncertainty surrounding the best estimate made for a particular variable, but, for a complete description of that uncertainty, a probability distribution is required. Thus in the final step of evaluation the designer estimates the probability distribution of each of the variables. The designer also can test the dependence of one variable on another and judge if the dependence can be ignored. Thus the algorithm is also designed to deal with dependencies which is very important in risk analysis. Finally the output from the risk simulation is the distribution of RFR or the risk profile. A risk profile does not definitely answer the question: should the investment be accepted or rejected? This would be impossible. An investment which is considered acceptable to a large organisation might well be considered too risky for a small organisation. A risk simulation does however provide a considerable increase in a decision maker's understanding of how different factors interact to form the total risk in the project. The thesis introduces two basic ideas which are new to computer aided ship design model, first the estimation of risk from sensitivity analysis and second, the calculation of risk profile of the measure of merit.

The risk simulation algorithm and the sensitivity analysis algorithm developed in this project are a set of standard algorithms which can be applied to extend ship design models developed for other ship types. It also contains an algorithm for generating a histogram type of risk profile on a line printer. Graphical plotting algorithms which are more sophisticated than the one used in the thesis can readily be incorporated.

Finally an accept or reject decision can only be made when a risk analysis is carried out. For comparing alternatives a deterministic approach with sensitivity analysis may be adequate, but once an optimum design has been found,
it is necessary to know the risk inherent in undertaking such a capital investment venture. Thus this suite of programs not only helps a Naval Architect to compare alternative designs but also helps him to study the acceptability of the final design.
CHAPTER 4

DEVELOPMENT OF CONTAINERISATION

4.0. INTRODUCTION

4.1. A SHORT PREVIEW OF HISTORICAL DEVELOPMENT

4.2. CHANGES IN STRUCTURE OF SHIPPING

4.3. ROUTE DEVELOPMENT

4.4. TECHNOLOGICAL DEVELOPMENT

4.5. CONTAINERS
4.0. INTRODUCTION

From the history of containerisation lessons can be drawn. Thus in this chapter an abbreviated overview of 'containerisation' is given. If we take the view that historical facts are nothing but the sum total of the experiences of successes and failures, then the empirical assimilation of experiences properly analysed provides an insight into the reasons for the successes and failures.

The chapter is basically divided into five subsections each concentrating on one aspect of containerisation. The first section is devoted to the various chronological developments, and it is noted that the container concept is not a new one, but it took quite a long time before it became a viable concept which could be applied. The second section shows how the shipping companies once able to operate independently, with the advent of containerisation were forced to combine or share their resources across their national boundaries. The third section discusses the new route developments and how wrong it is to assume that 'containerisation' will be slow to penetrate the trade between developed and underdeveloped countries. The fourth section deals with the technology involved in the containerisation and the main emphasis is on the container ships and how they evolved. The last section outlines the development of standardisation, the incorporation of certain other standards, the problem of nine high stacking, lashing of containers on deck and lastly the overtonnage in containers. The definition of the various types of unit load carriers is given in Table 4.1. In the thesis, only fully cellular container ships will be considered although the computer programs could be adjusted for container carrying ships without guides.
TABLE 4.1. Definition of unit load carriers.

<table>
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<td>FULLY CELLULAR CONTAINERSHIPS</td>
<td>These ships are designed to carry about 60% of the total container capacity under the deck in holds fitted with cell guides. The hold containers are stacked vertically one on top of another from 4 up to 9 high in the cell guides. The rest of the containers are carried on deck stacked up to 4 tiers high one on top of another and secured to the deck by lashings. The ships usually do not have any container handling cranes on board, the loading and the unloading of the containers being carried out by shore based container gantry cranes (13, 15).</td>
</tr>
<tr>
<td>ROLL-ON, ROLL-OFF SHIPS</td>
<td>A wide variety of ships are included in this category e.g. Passenger/vehicle ferries, short sea freight Ro-Ro's, deep sea Ro-Ro's, Car carriers, train ferries (15). These are designed to carry a wide variety of standard units, including containers which may be carried on trailers or by fork lift trucks, pallets, vehicles, loaded lorries as well as uncrated export cars, and large indivisible loads such as heavy plants (15). The holds are provided with large uninterrupted deck area, internal ramps and/or lifts. Loading and unloading is done either by ramps or by shipboard handling equipment/cranes (13, 15).</td>
</tr>
<tr>
<td>COMBINATION CARRIERS</td>
<td>These are designed primarily for carriage of roll-on-roll-off cargoes and cellular stowage of containers in one or more cargo holds (usually located forward). Container loading/unloading is usually done by means of shipboard travelling cranes (13, 15).</td>
</tr>
<tr>
<td>BARGE CARRIERS</td>
<td>These are designed to carry barges (lighters) each of which is capable of carrying about 300-850 tons of break-bulk cargo, palletised cargo, heavy loads and containers. The 'mother ship' which is the barge carrier loads and unloads barges, either by elevators/lifts or by the float-in</td>
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TABLE 4.1 (Contd.).

principle. The barge carrier can berth outside a port and the barges individually or in trains can then load and unload at shallower drafts, thus it reduces the need for any shore facilities (13, 15).

PALLET SHIPS - These ships are not designed to carry containers, but the general cargo is palletized forming a single unit, which can be easily handled by a fork lift truck. Pallets are not standardized but most are of about size 1.2 x 1.0 m wooden platforms. The pallets are loaded and unloaded through a side door (13, 15).
4.1. A SHORT PREVIEW OF HISTORICAL DEVELOPMENTS

Table 4.2 summarises the historical development of containerisation since its inception in 1906 to the first deep sea container service in 1968. This historical development is described briefly. Kunnerman (6) and Rath (7) give detailed historical development of all aspects of containerisation.

There is considerable evidence that the concept of containerisation was applied as far back as 1906, and was reported in the National Geographic magazine in April 1911 (5, 6). However the concept was not exploited on a large scale until about 1950.

Shortly after World War I, Charles Brasch organised Seatrain Lines to provide a railway wagon service by water between Cuba and the coast of the United States (7). His system was the first perhaps to exploit the deep sea route, and consisted of specially designed shoreside cranes equipped with trays with railroad tracks installed on them. The lack of cooperation of the railroads eventually led to the abandonment of this idea by Seatrain Lines (7).

On this side of the Atlantic large containers of various kinds have been used in inland and overseas distribution for many years. London Midland and Scottish Railways first used containers in 1926 and unit load systems have been a feature of Great Britain-Ireland trade since the Second World War (8).

It is debateable whether the effort to promote containerisation at the International Road Transport Congress in September 1928 or the presentation of a movie at the International Chamber of Commerce in May 1929 in the U.S.A. at the same time covering rail transport, had any significant influence on the overall development of containerisation (7).

The potentialities of containerisation were recognised on this side of the Atlantic also, when in 1931 the Royal Commission on Transport in the U.K. reported their surprise that the advantages of containerisation were not recognised by the shipping fraternity (8).
<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1906</td>
<td>First published evidence of application of concept of containerisation.</td>
</tr>
<tr>
<td>1916</td>
<td>Railroad car service by water from Cuba - coast of U.S.</td>
</tr>
<tr>
<td>1926</td>
<td>London Midland &amp; Scottish Railways used containers.</td>
</tr>
<tr>
<td>1928</td>
<td>International road transport congress organised a conference to promote the idea of containerisation.</td>
</tr>
<tr>
<td>1929</td>
<td>Promotion of idea of containerisation in May 1929 by International Chamber of Commerce by presentation of a movie, together with coverage of Rail Transport.</td>
</tr>
<tr>
<td>1931</td>
<td>Royal Commission of Transport in U.K. pointed out the advantages of containerisation in their report.</td>
</tr>
<tr>
<td>1933</td>
<td>Formation of Pan-Atlantic Steamship Corporation.</td>
</tr>
<tr>
<td>World War II</td>
<td>Use of 'conex' containers by the U.S. Army transportation corps and development of the first extensive container transport operation.</td>
</tr>
<tr>
<td>Post-war period</td>
<td>Resurgence of interest in containerisation by commercial operators.</td>
</tr>
<tr>
<td>1956</td>
<td>Building of first C3 class cargo ship by Maritime Commission, U.S. to carry containers.</td>
</tr>
<tr>
<td></td>
<td>Alaska becomes the first part of United States to take advantage of unitization.</td>
</tr>
<tr>
<td></td>
<td>Korean war gave a further boost to the containerisation.</td>
</tr>
<tr>
<td>1957</td>
<td>First commercial container operation started between New York and Houston by Pan-Atlantic Steamship Company in converted T2 tankers.</td>
</tr>
<tr>
<td>1957-1958</td>
<td>Converted C2 type vessel 'Gateway City' became the first Lift-on/Lift-off type of ship.</td>
</tr>
<tr>
<td></td>
<td>Pan Atlantic converted further 6 tankers after the initial success.</td>
</tr>
<tr>
<td>1959</td>
<td>Matson Navigation Co. introduced 6 - C3 type vessels converted to carry containers on the West Coast of U.S.A. to Hawaii.</td>
</tr>
<tr>
<td></td>
<td>Pan Atlantic became Sealand Services Inc. first container shipping company.</td>
</tr>
<tr>
<td>Year</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>1961</td>
<td>American Material Handling Society, American Society of Mechanical Engineers and American Standards Association (ASA) adopted the first standards for containers.</td>
</tr>
<tr>
<td>1964</td>
<td>Associated Steamships, Australian shipping line began a container service between Melbourne and Fremantle.</td>
</tr>
<tr>
<td>1965</td>
<td>International Organisation for Standardisation, ISO, adopted the ASA container size and strength standards. Sealand announced its intention to enter the transatlantic trade.</td>
</tr>
<tr>
<td>1966</td>
<td>First liner service introduced by Sealand Services Inc. between Europe and U.S.</td>
</tr>
<tr>
<td>1966</td>
<td>Japanese government announced marine development plans.</td>
</tr>
<tr>
<td>1967</td>
<td>International standards organisation agreement signed in Moscow.</td>
</tr>
<tr>
<td>1968</td>
<td>First purpose built container ship introduced on the North Atlantic route.</td>
</tr>
</tbody>
</table>
In 1933, the Waterman Steamship Corporation established a coastwise service designated as Pan-Atlantic Steamship Corporation, for handling of general cargo, which extended from Boston, Massachusetts to Houston, Texas, and serviced the major ports on the Atlantic Coast between these two ports (9). This was a crude form of containerisation, the more valuable and fragile cargoes were carried in protective cages or wooden boxes to deter pilferage and breakage as much as possible.

As we have seen above until World War II, containers of various forms and dimensions were used within the rail systems in Europe and America. A few attempts were made by small ship operators to consolidate their cargo into boxes primarily to avoid damage and pilferage.

However credit must go to the U.S. Army Transportation Corps for the development of the first extensive container transport operation during the war. Also an exhaustive analysis of the full spectrum of military cargo established the fact that approximately 40% of the total cargo could be containerised (10). The containers used during the war were called 'Conex' containers, they were small units and were handled by conventional cargo gear, namely derricks and tackles (6). Like the prewar period, the original decision during the war by the U.S. military was not based on strictly economic reasons. The main reason was the protection against mechanical damage and inclement weather, provided by the metal container. Thus the full economic potential of containerisation was not realised by the commercial shipping operators.

However, whether by coincidence or example, a sudden flurry of interest in containerisation also appeared in the shipping field in the early post-war period (10). It was realised that improved handling of general cargo in and out and within the ship was an economic necessity. Consequently during the 1950's detailed studies were made of existing methods of handling break bulk cargo, palletization, fork lift operation, improved cargo gear, hatch configuration,
roll on-roll off ships, containers and so on (5). The studies were aimed at the use of containers but these containers were relatively small units. Overlooked and not identified was a common denominator, a large enough unit in common use ashore that could be readily adapted to the ships. The railway wagon was one possibility and the highway trailer the other (6). Other factors which were overlooked were, that the ships were not designed to handle this type of cargo efficiently, with the result that the boxes were frequently damaged. There was also serious loss of cubic because, the containers were stowed in the wing spaces of 'tween decks and lastly the vexing problem of return cargoes, which were not available (10).

The U.S. Maritime Commission even built a C3-Class cargo ship with over deck bridge cranes capable of handling unit loads up to 30 tons, which were strikingly similar to the ship mounted cranes of today (10).

It was left to the ingenuity of the private shipowners to develop the containerisation system and show that it worked.

A U.S. stevedore contractor was the first to develop the use of 40 ft. containers for cargo, which was much bigger than what his predecessors had experimented with. The containers were carried in barges to Alaska. He experimented with double decking and with stacking, and was perhaps the first to prove that containerisation could be so effective that the attributes of the vessels themselves would be overshadowed by the economy obtained in unitization. Alaska was thus the first part of the United States to take the full advantage of unitization (7). At the same time, two commercial groups, one a trucker turned shipper and the other a non-subsidized steamship company were independently experimenting with the intermodel containerised sea transportation of goods (6). Their ingredients for the success were the same; large containers that could be married to over-the road equipment, could be lifted aboard the ship without the highway wheels, could be stacked in
cells aboard the ship and moved to their stowed position in a vertical direction only.

Also this breakthrough in sea going containerisation received its greatest impetus from increased trade between the United States mainland and the islands of Puerto Rico and Hawaii and later Alaska (5). Malcolm McLean, a trucker turned shipowner and founder of Sealand Services, stimulated by profit motive and annoyed by the restrictive state highway regulations, conceived the bold idea of carrying his trucks on a ship for the long haul from Florida to New York (10).

Since the highway vehicle was made up of easily separable units consisting of tractor, trailer and container, the ship need only carry the latter, with the use of wheeled highway components confined to the land segments of the system. So the modern container ship was born. This must be recorded as one of the most significant and remarkable innovations in the history of sea transport. Economics now had replaced protection as the principal motivation. High cargo handling productivity, with attendant reduction in direct labour costs and port time of the vessel, coupled with the low cost/ton mile at sea, spelled success. The increase in the size of the unit load represented a quantum jump and was able to eliminate many handlings at the system interfaces (10).

For the above reasons in 1956, Pan Atlantic the predecessor to Sealand Service Inc., fitted two T2 type tankers the 'Ideal X' and 'Almena' with elevated platforms above the tankers deck and was used for carrying 35 feet trailer vans between New York and Houston (6). Simultaneously, another study was made by the company of roll-on/roll-off trailer vans but was abandoned in favour of container ships (5).

After their experimental run, Sealand in 1957, converted a C2 type vessel to a lift on lift off ship, and 'Gateway City' became the world's first container ship (6).
This conversion was an absolute departure from anything contemplated before. Each container was stacked in cells one on top of another seven high, with vertical guides at four corners preventing them from toppling. The containers were fitted with corner castings with openings for the engagement of a bayonet type twist lock device for lifting with a crane suspended frame. The scheme used in this first vessel is essentially the same as used today with very little modification.

'Gateway City' was followed by five other sister ships, all coming into service between New York, Miami, Tampa and Houston.

Following the same pattern Matson Navigation Company for years a dominant shipper in the U.S. West Coast to Hawaii trade converted six of their C3 vessels to carry 75 containers on deck. Subsequently it was Leslie A. Harlander, who developed the carrying of containers in cell guides. Matson used 8' x 8' x 24' containers compared to Sealand's 35' because two 24' vans loaded on the chassis could be moved by one tractor under Californian Highway laws.

By 1959, Pan Atlantic became Sealand Service Inc., the first shipping company to adopt containerisation. In the next year, 1960, Matson converted one of its C3 vessels to a full container ship, the 'Hawaiin Citizen'.

Another shipping company Grace Lines converted two C2 vessels in 1959 to full container ships using 17 ft. containers, intended for South American service, New York to Venezuela. The early services multiplied rapidly; by 1960 an extensive range of ports on both the East and West Coasts of the U.S. were connected by the container ships of Sealand, while Matson built up a comprehensive set of sailings to and from Hawaii. Grace Lines service from New York to Venezuela was the first outside the protected U.S. coastal trade, but although the operations of all three U.S. companies continued to prosper, very little was done on the international front. There were early opposition to containerisation, Grace Lines two ships on their maiden
voyage in 1959 were held up because the stevedores in South American ports refused to unload them and the service was subsequently scrapped (6). In 1957 a similar fate was met by Sealand's 'Gateway City' on her first voyage to Puerto Rico (6).

Besides general cargo, other forms of cargo were also being containerised. In 1961, two T2 tankers were converted by Union Carbide for transportation of granular chemicals in special containers. These containers were 30 ft. long, of relatively heavy all-welded aluminium construction (6).

On the other side of the Atlantic in 1962, the Rochdale Report on British ports came to the conclusion that the British ports and possibly the British shipowners were less forward looking than their overseas U.S. competitors (8). However the most important stimulus was standardisation. Little interchangeability existed between the various forms and sizes of equipment developed by various railroads and shipping companies. As pointed out above container sizes varied from 17' to 40'. Lifting and securing fittings were all different. If this newly developed method of transportation were to have widespread success and its full benefits realized, standardisation had to be brought about. As far back as 1961 the American Standards Association (ASA) adopted container size standards and strength standards in 1962. The International Organisation for Standardisation (ISO) tentatively adopted the ASA standards in all aspects except the strength standards which were based on stacking containers four instead of six high (5). The final agreement of container standardisation was signed in Moscow as late as June 1967 (8). In addition to the main purpose, that of easy interchange, the subsidiary benefits of standardisation include lower cost of the container through mass production and the opportunity to standardize transport vehicles and transfer equipment (6). In compromising spirit Sealand released for royalty free use, a key patent having to do
with the container corner fittings and making twist lock lifting fitting (6). Ironically the standards adopted by ISO omitted the Sealand's 35 ft. size as well as the 24 ft. used by Matson.

During 1962-1965 many container ships were built or converted in the U.S.; these included 16 conversions by Sealand; 4 by Matson (2 new buildings) and 20 other vessels either of full or part container capacity by several other American shipping companies (6). The Americans had realized the potentialities of containerisation while European ship owners remained sceptical. The Australian shipping line, Associated Steamships, was however an exception, which began in 1964 a container service between Melbourne and Freemantle with the first specially built container ship 'Kooringa' (6).

In the meantime in 1966 Sealand obtained the largest shipping contract ever awarded by the U.S. Government for the supply of military hardware to Vietnam (6). This provided a considerable stimulus to shipping lines; in fact a large part of Sealand's revenue came from military contracts. Thus the Korean war and subsequently the Vietnam war provided a much needed impetus to containerisation.

In the same year 1966, Sealand and U.S. lines put converted container ships into Transatlantic service. Hitherto it was U.S. coastwise and Puerto-Rican service only (6). In 1966 there were 5 shipping lines operating container services from the U.S. In January 1967, it was reported that there were 38 lines serving over 100 ports in Europe, Latin America, the Near East, the Far East, Africa, Australasia from the U.S. East and West Coast and Great Lakes ports (8). The step of Sealand to enter the North Atlantic route certainly removed any doubt from the minds of those who were hesitating about containerisation as reflected in the growth in containerisation after 1966.

The year 1966 also marked the commitment of many European owners to container services including Overseas Containers Ltd. (OCL), Associated Container Transportation (ACT),
Atlantic Container Line (ACL) and Johnson Lines (6). This also heralded an era of new buildings in container ships, specialist ships which were designed to carry only containers, i.e. fully cellular container ships. By June 1969 the number of lines had risen to 88, and the number of ports served to almost 200 (8).

Table 4.3 gives the differing views of different generations of container ships. Fig. 4.1 gives the chronological change in the principal dimensions, power, speed and carrying capacity of the different generations of the container ships. Table 4.4 outlines the chronological development of fully cellular container ships since 1960 for ships over 500 Teu. Table 4.4 shows that the first purpose built container ships came into operation in 1968, these were the first generation container ships. There were equal numbers of conversions in that year and the size of these vessels were about 835 Teu. The size of the purpose built were about 1000 Teu. 1969-71 saw the advent of the second generation container ships of 1000 Teu and the average size of purpose built container ships was about 1200-1300 Teu. The third generation container ships came into operation in 1972 with an average size of purpose built container ship of 1800 Teu. This was also the year when the highest numbers of container ships were built. After the oil crisis of 1973-74, the number of container ships to come into operation fell to 11 in 1975. It was not until 1977-79 that there was again a resurgence of new building activity. The size of the vessel was the same as those of the second generation ships about 1200-1300 Teu.

In the early years, port throughputs have increased very much in line with the growth rates of the container carrying fleet capacity (27). Quite naturally in the early years of the intercontinental containerisation involving the major liner trade routes growth rates were higher (between 1966-1973) than during the subsequent period until 1979. During the former, container throughput doubled

*Teu (Twenty Foot Equivalent Units). All container spaces in a ship can be expressed as 20 ft. equivalent spaces, e.g. one 40 ft. container is equal to 2 Teu's.
TABLE 4.3. Definition of different generations of cellular container ships. (From various articles)

<table>
<thead>
<tr>
<th>(12)</th>
<th>Capacity TEU</th>
<th>DWT tons</th>
<th>Loa m</th>
<th>Bext m</th>
<th>d m</th>
<th>V knots</th>
</tr>
</thead>
<tbody>
<tr>
<td>First generation</td>
<td>750</td>
<td>14000</td>
<td>180</td>
<td>25.0</td>
<td>9</td>
<td>22-23</td>
</tr>
<tr>
<td>Second &quot;</td>
<td>1500</td>
<td>30000</td>
<td>225</td>
<td>29.0</td>
<td>11.5</td>
<td>26-27</td>
</tr>
<tr>
<td>Third &quot;</td>
<td>2500-3000</td>
<td>40000</td>
<td>275</td>
<td>32.0</td>
<td>12.5</td>
<td>22-23</td>
</tr>
</tbody>
</table>

Year of Introduction

1966

"The first generation of major container ships were built in the late sixties for the Australian trade having container capacities up to 1500 TEU's and service speed around 22 knots from a single shaft arrangement". (16)

"These were ships of length between 175-200 m, with single screw arrangement, developing horse power between 28000-34200 PS and average speed of 23 knots with container capacity less than 1000 TEU". (17)

1971

1972

"The second generation ships were two- or three shafts arrangement and power supplied by steam turbine, gas turbine or three slow speed diesel engines and a container capacity of approximately 2500 TEU's. These were mainly introduced in early 70's for the Far East/ Australian trade." (16)

"The second generation of container ships are characterized by larger size about 245-273 m. in length, higher propulsion power about 70000-80000 PS, higher service speed about 26-27 knots and larger container capacity about 1800-2300 TEU". (17).
1977 "The third generation of container ship came about after the oil fuel crises in 1973. The initial success of 2nd generation of ships was greatly reduced by world-wide inflation and high fuel prices resulting in operation at reduced speed. Thus a slower, shorter but equal container capacity to 2nd generation was developed". (16).

The third generation are again the handy sized single screw ships with almost the same dimensions, power and speed as the 1st generation but designed with more stress on economical aspects, such as larger container carrying capacity and higher propulsive performance. (17).

Klaus Hoppe (13) however has a different viewpoint:--

"He defines the first generation vessels as those built during 1968 with 700-900 TEU. In 1970 the first of the so-called second generation about 1200-1700 TEU were put into service. In 1972 the third generation of container ship came into service about 2300-3000 TEU. A further development of still bigger and faster container vessels of the fourth generation was no longer followed up during or after the oil crisis. There developed the so called new second and new third generation of about 1100-1900 TEU as vessels of this size had been proved to be the most suitable for requirements of the trade".
Fig. 4.1. Chronological change of principal dimensions, power, speed and container capacity (17). (Japanese built)
<table>
<thead>
<tr>
<th>Year Build</th>
<th>Number of ships</th>
<th>Cargo Capacity in TEU</th>
<th>Average TEU per vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Purpose Built</td>
<td>Converted</td>
<td>Total</td>
</tr>
<tr>
<td>1960</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>61</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>62</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>63</td>
<td>-</td>
<td>-</td>
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<tr>
<td>64</td>
<td>-</td>
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<td>-</td>
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<td>3</td>
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<td>68</td>
<td>15</td>
<td>11</td>
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</tr>
<tr>
<td>69</td>
<td>21</td>
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<td>70</td>
<td>18</td>
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<td>71</td>
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</tr>
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<td>72</td>
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<td>9</td>
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<td>73</td>
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<td>31</td>
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<tr>
<td>74</td>
<td>14</td>
<td>-</td>
<td>14</td>
</tr>
<tr>
<td>75</td>
<td>7</td>
<td>4</td>
<td>11</td>
</tr>
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<td>76</td>
<td>18</td>
<td>-</td>
<td>18</td>
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<td>77</td>
<td>41</td>
<td>7</td>
<td>48</td>
</tr>
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<td>78</td>
<td>44</td>
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<td>79</td>
<td>41</td>
<td>22</td>
<td>63</td>
</tr>
<tr>
<td>80</td>
<td>37</td>
<td>7</td>
<td>44</td>
</tr>
<tr>
<td>Total</td>
<td>361</td>
<td>123</td>
<td>486</td>
</tr>
</tbody>
</table>

Compiled from (14) containerships over 500 TEU as on November 1, 1980.
every 15 months on average, while after 1973 the growth slowed to an average duplication period of around $3 \frac{1}{2}$ years (27). The growth rate for container demand will be in line with the global gross national product (GNP) (26). It is apparent that future expansion of containerisation will be in tapping the potential of the developing world which will be very much dependent on the provision of port and other facilities (27). In line with limited or zero growth rates in general economic activity of the developed world, the primary container routes will only generate modest container volume increases.

Wing and Hillman (32) give a clear exposition of the trade forecasting techniques which can be used to project the future demand and supply of general cargo vessels. Turnbull (33) based on these forecasting techniques estimates that between 1980-85 the number of general cargo vessels required per annum would be 500 assuming an average size of 16000 dwt and this would fall to 450 ships per annum between 1985-90.

4.2. CHANGES IN STRUCTURE OF SHIPPING

One of the main effects of containerisation has been to radically alter in little more than a decade, the profile of the world cargo liner fleet, as well as the structure and the operating practices of most of the world's major cargo liner shipping companies.

Before the advent of container ships in the early 1960's the general cargo trade or break bulk trade was carried by and large in the scheduled services of cargo liners. When business was good two deck tramp ships were often chartered to 'double head' the berth and sometimes even three ships in all would carry out a given cargo liner scheduled sailing. Occasionally with break bulk cargo a tramp ship would be chartered to travel between two ports, as was common for bulk commodities and could offer a lower freight-rate. The main impact of the container ship was on cargo liner operation and had replaced it in the major trades by the late seventies.
As the container ship numbers increased the number of cargo liners decreased and this decrease during the period 1970-1973 was equivalent to one container ship replacing four conventional general cargo vessels (11). This is because a container ship is much more efficient in terms of cargo carrying capacity, e.g. a cargo liner built in 1966 has $870 \times 10^6$ dwt tonne miles/annum compared to $5612 \times 7.06 \times 10^6$ dwt tonne miles/annum of a container ship built in 1972, a factor of 6.45 (9). Although the cargo liner has seen a change in style it has not disappeared ten years later, since the container ship arrived in 1969. Meek (13) points out that the simpler the ship is to design and construct, the better it will be to provide an economic return; and the way to obtain a simple ship is to allocate to it a single cargo type. Thus the cargo liner of today is a less sophisticated vessel carrying cargoes which are not yet containerised. So the first effect of containerisation has been to shrink the total number of ships required to carry the general cargo trade.

While the Americans worried about the tooling up of containerisation, Olof Wallenius, a leading shipper of automobiles worried about how to finance the economy of scale. The recognition of the size of the ship investment required to be effective in containerships led Wallenius in the mid sixties to offer the idea of "Consortium" to many shipowners. His offer to the United States lines had to be rejected because of the Anti-trust legislation in America and the subsidy nationality issue (7).

But Cunard Lines (Great Britain), French Lines (France), Holland-America Lines (Netherlands) and two Swedish Lines, Swedish Transatlantic and Swedish Lines formed the world's first consortium with Wallenius Lines (7).

British and Japanese owners were well established in the liner trade, thus they could easily make the transition from conventional to container operations without recourse to international partnership (11).
While the Japanese and the Americans were slow to the idea of consortia, a majority of Scandinavian and Continental shipowners motivated by recognition of the implications of economy of scale in the construction and operating stages and identification of the massive capital investment this would call for, formed consortia to pool their resources (7) similar to OCL and ACT.

Thus the Wallenius idea of amalgamation of shipping interests has proven to be the greatest institutional change in world shipping. Joint services became most significant in areas where the largest ships and most containers were required.

The effect of containerisation on port development has also been significant. During the last 10-15 years port authorities all over the world have invested heavily in container facilities. This investment was brought about without coordination at a national and international level. The number of container/Ro-Ro berths rose from zero at the end of 1975 to 55 by the end of 1983 in the Arabian Gulf alone (11).

The rush of new buildings during 1968-1973 (Table 4.4) while containerisation was establishing itself in major trade routes may be one of the factors in the overinvestment in ports. The rush in new buildings was followed in 1974-1975 by a slump of orders which was mainly due to the oil crisis, the onset of recession and overtonnage in certain routes. Overtonnage on trans-Pacific trades led to mass resignations from conferences in 1975 and to rate competition severely affecting the profitability of certain shipping companies (11).

To summarise we can say that with the advent of containerisation fewer but more expensive ships were needed in the general cargo trade which called for heavy investment in ship and port facilities. To offer the door-to-door concept of delivery required pooling of resources of various shipping companies across their national boundaries by formation of consortia.
4.3. ROUTE DEVELOPMENT

Table 4.5 outlines the chronology of service inauguration of cellular container ships since the advent of containerisation. Table 4.6 gives the characteristics of the container ships on major trade routes. The maximum number of ships are on the West Coast of North America - Far East (WCNA-FE) and the Europe-Far East (Eur-FE) routes. The largest number of non-conference operators are on the WCNA-FE and the Northern Europe-Middle East (N.Eur-ME) route. The largest ships are on the N.Eur-FE and the N.Eur-South African route. Influence of the Panama Canal beam restriction of 32.30 m is evident in many routes connecting Europe and North America to the Far East, Europe-North America and the South African routes. The principal trade routes are shown in Fig. 4.2 together with the year they came into service. Drewry (11) gives the historical development of principal trade routes and Kieselhorst (26) gives statistical analysis of different trade routes together with the potential for further containerisation of these routes. A brief summary of the salient points of these trade routes is given here.

In no more than seven years containerisation has captured the liner trades between the developed continents e.g. North America, Europe, Australia and the Far East. Although as early as 1972 the first developing countries were integrated into the network connecting the Far East to the developed nations of the West (26), the relative share of the developing world in terms of total port handlings arose from under 5% in 1971 to around 24% in 1978 (26). There has also been an increase in the relative share in port handlings of the Far East and South East Asian countries from about 9% to over 24% during the same period. The global growth rate has been around 15% to 17% whereas the growth rate between the developed world has declined from about 32% in 1972 reaching its peak in 1974 to about 6-7%/annum in 1978. In the developing world there has been a sustained growth rate of around 18 to 19%/annum. Therefore

* Container growth rates in fleet deployments or port throughput in percentage per annum.
TABLE 4.5. Chronology of service inauguration of cellular containerships (26).

<table>
<thead>
<tr>
<th>Year</th>
<th>Route Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1955</td>
<td>United States coastal services</td>
</tr>
<tr>
<td>1958</td>
<td>North America - Hawaii</td>
</tr>
<tr>
<td>1959</td>
<td>Australian coastal services</td>
</tr>
<tr>
<td>early 60's</td>
<td>New Zealand coastal services</td>
</tr>
<tr>
<td>1963</td>
<td>North American East Coast - Puerto Rico</td>
</tr>
<tr>
<td>1964</td>
<td>North American West Coast - Anchorage</td>
</tr>
<tr>
<td></td>
<td>Australia/New Zealand</td>
</tr>
<tr>
<td>mid-60's</td>
<td>European coastal services</td>
</tr>
<tr>
<td>1966</td>
<td>North American East Coast - North Europe</td>
</tr>
<tr>
<td>1968</td>
<td>North American West Coast - Far East</td>
</tr>
<tr>
<td></td>
<td>Canadian Atlantic - North Europe</td>
</tr>
<tr>
<td>1969</td>
<td>Australia - Europe</td>
</tr>
<tr>
<td></td>
<td>Australia - North American East Coast</td>
</tr>
<tr>
<td></td>
<td>Australia - Far East</td>
</tr>
<tr>
<td></td>
<td>North American West Coast - North Europe</td>
</tr>
<tr>
<td></td>
<td>North America/Atlantic - Mediterranean</td>
</tr>
<tr>
<td>1971</td>
<td>Australia/New Zealand - North American West Coast</td>
</tr>
<tr>
<td></td>
<td>Mediterranean - North American West Coast</td>
</tr>
<tr>
<td>1972</td>
<td>Europe - Far East</td>
</tr>
<tr>
<td></td>
<td>North Europe - United States-Gulf</td>
</tr>
<tr>
<td>1973</td>
<td>North America - Indian Subcontinent</td>
</tr>
<tr>
<td></td>
<td>Mediterranean - Far East</td>
</tr>
<tr>
<td>1975</td>
<td>Europe - South Pacific</td>
</tr>
<tr>
<td></td>
<td>Europe - Middle East</td>
</tr>
<tr>
<td></td>
<td>North America - Middle East</td>
</tr>
<tr>
<td></td>
<td>Europe - Morocco</td>
</tr>
<tr>
<td>1976</td>
<td>Far East - South Pacific</td>
</tr>
<tr>
<td></td>
<td>North Europe - Caribbean/Central America East Coast</td>
</tr>
<tr>
<td></td>
<td>North American Atlantic - West Africa</td>
</tr>
<tr>
<td></td>
<td>Miami - Ecuador</td>
</tr>
</tbody>
</table>

27
<table>
<thead>
<tr>
<th>Year</th>
<th>Routes</th>
</tr>
</thead>
</table>
| 1977 | North America/Far East - Panama/Venezuela  
Australia/New Zealand - Middle East  
Australia - Sri Lanka  
Australia/New Zealand - South East Asia  
Europe - South Africa  
Europe - West Africa  
Europe - Indian Subcontinent/Indonesia  
Europe - New Zealand  
Far East - Middle East  
Australia - South East Asia  
Australia - Papua New Guinea  
Mediterranean/Caribbean  
South American East Coast - Coastal services |
| 1978 | North American Atlantic - South American East Coast  
Brazil - West Africa  
North American West Coast - South Pacific  
North Europe - Central American West Coast  
North American West Coast - Central American West Coast |
| 1979 | North Europe - Mexican Atlantic  
Mediterranean - Venezuela/Mexican Atlantic  
Europe - Mozambique  
North American Atlantic - Colombian Atlantic |
| 1980 | North Europe - South American East Coast  
Far East - Indonesia  
Australia - South Africa  
China - Australia  
China - Europe  
Black Sea - India  
North Europe - Sri Lanka/India  
Australia/New Zealand - (South American West Coast)  
Venezuela/Caribbean  
Mediterranean - East Africa |
| 1981-82 | Far East - South Africa  
Europe - Indonesia |
| 1982 | Europe - South American West Coast |
|-------|-------------|-------------------|-------------|------------|------|-------|------|------|------|------|------|------|------|------|
| 1. North Europe – North America | 31 | 456 | 1968 | 17 | 17 | 14 | 6.5 | 9.5 |
| 2. U.S. east coast – North America | 3 | 560 | 1070 | 16 | 16 | 15 | 9.5 | 11.5 |
| 3. North Europe – Mediterranean | 7 | 560 | 1214 | 18 | 18 | 17 | 7.7 | 9.5 |
| 4. Europe – Far East | 20 | 1604 | 1950 | 21 | 21 | 20 | 11.7 | 13.0 |
| 5. West Coast North America – | 67 | 492 | 1800 | 17.5 | 17.5 | 16.5 | 8.4 | 9.6 |
| 6. East Coast North America – | 2 | 860 | 1897 | 20 | 20 | 19 | 9.4 | 10.4 |
| 7. Australasia | 1 | 544 | 1748 | 16 | 16 | 15 | 8.3 | 10.7 |
| 8. East Coast Australasia | 11 | 750 | 1708 | 19 | 19 | 18 | 9.4 | 11.5 |
| 9. Australasia | 11 | 550 | 1309 | 15 | 15 | 14 | 8.3 | 10.6 |
| 10. East Coast – Australasia | 4 | 430 | 1040 | 15 | 15 | 14 | 9.3 | 11.1 |

C = Conference operators
NC = Non-conference operators

Contd.
### TABLE 4.6. (Contd.).

<table>
<thead>
<tr>
<th>No. of ships</th>
<th>TEU container capacity</th>
<th>Knots speed</th>
<th>metres length</th>
<th>Ext. beam</th>
<th>Draft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>NC</td>
<td>Min.</td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>16. North Europe -</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>1202</td>
<td>-</td>
</tr>
<tr>
<td>Caribbean</td>
<td>4</td>
<td>-</td>
<td>581</td>
<td>630</td>
<td>15</td>
</tr>
<tr>
<td>17. U.S. East Coast</td>
<td>6</td>
<td>-</td>
<td>900</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td>Caribbean</td>
<td>2</td>
<td>-</td>
<td>410</td>
<td>-</td>
<td>16</td>
</tr>
<tr>
<td>18. North Europe -</td>
<td>7</td>
<td>-</td>
<td>1566</td>
<td>1654</td>
<td>22</td>
</tr>
<tr>
<td>West Africa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19. Mediterranean -</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Far East Australia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20. Mediterranean -</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North America - Far</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East America</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C - Conference operators
NC - Non-conference operators

(Compiled from Ref. (11))
it can be inferred that there is no untapped potential for containerisation in the developed world. The growth of containerisation will come from new routes to developing countries. These emerging regions together with their high growth rates/annum are; Africa (62%), Latin America (47%), Middle East (76%), Indian subcontinent (179%) and the South Pacific (611%). However routes to these emerging regions as potential for containerisation can only come about if the port infrastructure can be provided, until then the growth will be sustained at the current level of around 4%/annum. Estimating available future potentials requires an appraisal of the situation in the various major world regions. These regions are briefly reviewed below.

Europe Mediterranean:
The growth in port throughputs until 1973 was largely due to the finalisation of the first phase of containerisation on major trade routes i.e. North America, Australia/New Zealand and the Far East. In that year the Far Eastern regions contributing nearly 60% of the tonnage for that year. This growth declined after 1974 principally due to the fuel oil crises and low level of economic activity. Further growth in ensuing years was sustained by inauguration of new routes to the developing countries i.e. Middle East, Africa, the Carribean and the South Pacific. This area has considerable untapped potential especially in short sea trades.

North America:
In respect of deep sea trade routes North America is less diverse than Europe-Mediterranean as only two major routes, Europe/Mediterranean and the Far East account for 78% of the 1980 deep sea container fleet employed in American waters.

Growth rates are lower than Europe due to the predominance of the above cited trade routes whose container potentials seem to be already exploited.

There are extensive land bridges across North America and the Pacific ports have profited more from the land-bridging than others, this is because of the huge

* High growth rate per annum caused by low base value.
Asian trade and the Australia/New Zealand route. But now the new container routes to the Middle East, Latin America and Africa will again strengthen the Atlantic side.

Far-East and South East Asia:

Of all the major container trading regions, the Far East/South East Asia have contributed most to the rapid growth of containerisation. Growth rates in port throughputs have been above average.

North America, Europe/Mediterranean and Australia/New Zealand still account for more than 90% of the container fleet activity in this area.

Since 1975 countries like Hong Kong, Taiwan, S. Korea and Singapore had a growth rate higher than Japan which at that time controlled nearly 50% of the containers handled.

Although Thailand, Philippines, Indonesia, Malaysia and China still have large untapped potential, future growth may not come from these regions because of slow economic activity and port development programmes. Most of the growth will therefore be sustained by the economic activity of Japan, Hong Kong, Taiwan, South Korea and Singapore which accounted for more than 90% of the region's container activity.

Australia/New Zealand:

Overall growth rates have been more continuous than in other regions both in terms of fleet deployment and port throughput.

Australia overcame the recession which affected all other regions by advancing containerisation of its Asian trades. New services were also introduced in 1977 notably between Europe and New Zealand.

This area's potential for growth will not be dramatically changed by the introduction of new routes since most of the cargo has already been containerised.
Middle East:
This region has in recent years shown the largest growth rates and will continue to sustain high growth rates because of their low resources of industrial and agricultural goods. It is estimated that by 1980 only 15% of the total estimated potential has been tapped. But the speed of containerisation of the available potentials will be largely governed by the development of ports.

Africa:
In recent years major events in intercontinental containerisation were the full scale conference coordinated containerisation of the South African trade in 1977 and the progressive containerisation of the West African trade (see Fig. 4.2). There has been a considerable amount of reefer installations in fully cellular container ships in the South African trade whereas West African trade has been hampered by lack of adequate port facilities. This explains the smaller ship sizes and the high proportion of non-cellular tonnage (Ro-Ro and semi-container ships) in this trade.

Latin America:
This area has also been identified as a major growth area. Full scale containerisation has yet been limited to the Caribbean and Central America, while Mexico and the South American continent remain largely untapped. Apart from one Ro-Ro operation with the United States, the tonnage employed is essentially composed of semi-container ships.

Indian Subcontinent:
The Indian subcontinent is the last but not the least significant area where containerisation will advance. Apart from semi-container tonnage all types of small and large container carrying ships can be found on this continent, involving all major trade routes, including coastal operations. Because of the proximity to busy container routes this region
can be quickly containerised as soon as adequate port facilities are built.

Having discussed the growth of containerisation and potential for future growth, it is necessary to see this against the overall trade in dry cargo.

The liner transport related to the dry cargo section of the world trade was 22.3% in 1965 and fell to 18.5% in 1972 with 17.2% forecast for 1985\(^{(18)}\). Also the liner transport failed to participate in the trade growth to the same extent as non-liner dry cargo ships. While container cargo grew in absolute terms and steadily increased its market share in the liner section, conventional liner cargo fell drastically in absolute terms.

4.4. TECHNOLOGICAL DEVELOPMENT

The technological development of container ships has reflected experience in operation giving rise to many improvements in detail and economies of scale which have been reached by considerable increase in size. Values of Froude number did not change much from the first to the second generation indicating that the same relative speed was sought, although the absolute value increased by a few knots. From the second to the third generation Froude number fell indicating the effect of much higher fuel costs and the relatively high speeds of the second generation of container ships may not return. Some of the problems associated with the container ships and their subsequent improvement over the years are discussed in this section.

The initial problems to be resolved when the first generation of container ships were being built were

(a) Actual weight of an average loaded container was not known, although the maximum permissible weight was known \(^{(18, 19)}\).
(b) The optimum clearance between cell guides and containers were not known \(^{(18, 19)}\).
(c) The optimum deck width at side to meet the strength requirements.
(d) Other structural problems related to open type of ships (20, 21, 22, 23) such as,

(i) Necessity of obtaining the same section modulus against longitudinal bending with considerably reduced deck plating.

(ii) Concentrated loading on the double bottom.

(iii) Reduction in support of side framing due to reduced width of deck plating.

(iv) An 'open section' lacks torsional rigidity and is prone to warp, causing additional longitudinal stresses which augment those due to longitudinal bending.

(e) There were problems related to propulsive performance, seakeeping quality, manoeuvrability and propellers designed to deliver the high horsepowers. Investigation into these problems are outlined in Table 4.7 for the different generations of container ships.

(f) Improvement in stability characteristics were needed due to the larger deck loading of containers as ship size, constrained by the Panama Canal dimensions and the speed increased (13).

An interesting study of the trends in containership design is presented in (24) and some of the article is reproduced in the following pages. Unfortunately the word improvement is often used whereas the word change could be more appropriate. Some of the changes mentioned in the article are the results of economies of scale or differences in Froude Number. Among these effects however, will be the steady improvement in structural arrangement, hull form, hull surface finish and machinery over period 1968 to 1976.
### 1. Major items of investigations for development (propulsive performance, seakeeping, maneuvrability and propeller design) (17)

<table>
<thead>
<tr>
<th>Ship</th>
<th>Propulsive performance</th>
<th>Propeller</th>
<th>Maneuvrability</th>
<th>Seakeeping quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st generation ships</td>
<td>Application of wave resistance theory</td>
<td>Application of propeller theory, Study on propeller with modified pitch ratio and expanded area ratio, Study on strength of blade.</td>
<td>Application of strip theory and wave statistics, Advancement of model test technique, Full scale tests in service.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Study on flow around a propeller by wake survey</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd generation ships</td>
<td>Application of wave resistance theory, Development of new hull form</td>
<td>Study on hydrodynamic characteristics of large sized bossings, Development of slender shaped bossing</td>
<td>Comparative study on rudder and propeller configurations.</td>
<td>The same as above</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The vehicle efficiency (VE) may be defined as the necessary energy for transporting cargoes a certain distance. This can be expressed as (24)

\[
VE = \frac{\text{Number of containers or weight of cargo} \times \text{distance}}{\text{Specific fuel consumption} \times \text{power} \times \text{time}}
\]

\[
= \frac{N \times \text{dist.}}{\text{Sfc} \times \text{SHP} \times \text{dist.}} \propto \frac{N \times V_s}{\text{Sfc} \times \text{SHP}}
\]

where SHP = horse power in PS

\(V_s = \text{service speed in knots and}

N = \text{container capacity in Teu.}

If we take the specific fuel consumption to be constant

Then \(VE \propto \frac{N \times V_s}{\text{SHP}} \) or \(\left(\frac{\text{SHP}}{\Delta V_s}\right)^{-1} \times \left(\frac{N}{\Delta}\right)\)

where \(\Delta = \text{displacement on tons.}\)
The two parameters $\frac{\text{SHP}}{\Delta V_s}$ and $N/\Delta$ are used to trace the development of containerships (24, 25, 17).

4.4.1. $\frac{\text{SHP}}{\Delta V_s}$ (24).

If we denote $\frac{\text{SHP}}{\Delta V_s} = K$, then the factor $K$ denotes the energy consumption per ton-mile. The value of $K$ is plotted against speed in Fig. 4.3 for the conventional cargo liners, first generation of container ships and the current generation of container ships. It is evident that the energy consumption per ton mile has progressively decreased from the cargo liners of the early years to the container ships of today. The improvement in the hull form can be shown by expressing $\frac{\text{SHP}}{\Delta V_s} = \frac{R}{\Delta} \alpha C V_s^2$ where $R$ is the drag and $C$ is the drag coefficient. The value of $\frac{(\text{SHP})}{\Delta V_s} \times \frac{1}{V_s^2}$ which is proportional to $C$ is plotted against the service speed and shown in Fig. 4.4. It is evident that the drag coefficient $C$ has decreased for the current generation of container ships and the difference between each straight line represents this improvement.

To see the improvement in the factor $K$ for different sizes of container ships, $\frac{\text{SHP}}{\Delta V_s}$ was plotted against service speed $V_s$ for ships of different size and is shown in Fig. 4.5. These straight lines can be given by the following equation

$$\frac{\text{SHP}}{\Delta V_s} = (8.80 - 1.243 \times B + 2.653 \times V_s) \times 10^{-2}. \text{ PS/ton-mile}$$

Thus larger breadth and lower speeds gives lower values of energy consumption/ton-mile.

4.4.2. $N/\Delta$ (24).

In the case of conventional cargo liners the deadweight/displacement ($\text{dwt}/\Delta$ ) ratio decreases as the speed increases. If we denote the dwt as similar to container capacity $N$, then in the case of container ships the value of $N/\Delta$ increases as the speed increases or the displacement increases. This can be partly explained by the fact that as the speed increases, the hull form becomes finer and in the case of a

* PS= metric horsepower
Fig. 4.3. The effect of improvement in Energy Consumption (24).

![Graph showing the effect of improvement in Energy Consumption](image)

Fig. 4.4. The effect of improvement of ship hull form (24).

![Graph showing the effect of improvement of ship hull form](image)
Fig. 4.5. The effect of improvement in $K$ on the ship size (24).

![Graph showing the effect of improvement in $K$ on the ship size](image)

Regression Equation

$$\frac{\text{SHP}}{\Delta V} = (8.80 - 1.243 \times B + 2.653 \times V) \times 10^{-2}$$

Service speed $V$ in knots.

Fig. 4.6. $\frac{N}{\Delta}$ versus speed and displacement (24).

![Graph showing $\frac{N}{\Delta}$ versus speed and displacement](image)

Service speed $V$ in knots

Displacement $\Delta$ in tons
conventional cargo liner its ability to carry more dead-weight becomes limited. Whereas the container ship can achieve higher speeds by carrying some of the containers on the deck from the hold thus allowing it to achieve a finer hull form. Fig. 4.7 shows the improvement in $N/\Delta$ as the deck tiers of containers are increased.

4.4.3. \text{SHP/NV}_s (24).

Now combining $\left(\frac{\text{SHP}}{\Delta \text{NV}_s}\right)$ and $\left(\frac{N}{\Delta}\right)^{-1}$ we have $\frac{\text{SHP}}{\Delta \text{NV}_s}$. The improvement in the vehicle efficiency due to speed increase for container ships of different sizes is shown in Figure 4.8. It is evident that the vehicle efficiency is improved as the size and speed of the ship increases. Fig. 4.9 shows the vehicle efficiency plotted against ship size for container ships of different speeds. In Fig. 4.8 the container ships of different sizes have similar slopes indicating a gradual improvement and similarly in Fig. 4.9 the container ships of different speed shows gradual improvement in the vehicle efficiency $\frac{\text{SHP}}{\Delta \text{NV}_s}$ as the speed increases.

4.4.4. Reduction in hull steel weight (24).

In order to analyse the trend of hull steel weight the coefficient $\frac{\text{WH}}{(L \times B \times D \times C_b)} (t/m^3)$ was plotted against the date of delivery as shown in Fig. 4.10 where WH = weight of steel hull in tonnes. As the number of rows of hatchways increases the hull steel weight WH increases. The trend of the hull steel weight as shown in Fig. 4.10 is given by:

for container ships

\[
\frac{\text{WH}}{L \times B \times D \times C_b} = 0.232 + 0.135 \times r_H + 0.00525 \times \frac{L}{D} - 0.00228 \times \text{del} \quad \text{t/m}^3 \quad \text{Eq. (4.1)}
\]

and for cargo liners

\[
\frac{\text{WH}}{L \times B \times D \times C_b} = 0.155 + 0.00538 \times r_H + 0.00589 \times T_D + 0.00242 \times \frac{L}{D} - 0.00107 \times \text{del} \quad \text{t/m}^3 \quad \text{Eq. (4.2)}
\]
Fig. 4.7. Improvement in $N/A$ contributed by the deck loading (24).

![Graph of Container capacity $N$ vs. $L \times B \times D$ in m$^3$.]

Fig. 4.8. $\frac{SHP}{NV_S}$ versus speed $V_s$ (24).

![Graph of $\frac{SHP}{NV_S}$ vs. service speed $V_s$ in knots.]  
- 700-900 Teu
- 1000 Teu
- 2000-2300 Teu
- 1400-1500 Teu
- 1800-1900 Teu

Fig. 4.9. $\frac{SHP}{NV_S}$ versus capacity (24).

![Graph of $\frac{SHP}{NV_S}$ vs. container capacity $N$ Teu.]  
- 22-23 knots class
- 25 knots class
- 26-27 knots class
Fig. 4.10. Reduction in hull steel weight (24).

- Container ship shallow depth type: $r_H = 3$, $L/D = 12.0$
- Container ship deep depth type: $r_H = 2$, $L/D = 11.0$
- Cargo liner: $r_H = 1$, $L/D = 11.5$
- $r_H = 1$, $T_D = 3$, $L/D = 12$

Hull steel weight ($W_H/L \times 8 \times 8 \times C_D \times t/m^3$) vs. Year of delivery (del)
where \( r_H \) = number of hatchways, \( T_D \) = number of decks, and \( \text{del} \) = date of delivery in years A.D. e.g. a ship delivered in 72 October is expressed as 72.83 etc.

It is evident that there has been progressive decrease in the hull steel weight of container ships and the rate of decrease is twice that of a cargo liner. If the hull steel weight is plotted as \( N/WH \) against the year of delivery then the number of containers/t \( (N/WH) \) of deep depth type vessel will be less than that of the shallow depth type \( (24) \).

Table 4.8 outlines the major characteristics of the fully cellular container ship of different sizes. The influence of the Panama Canal constraint on length, beam and draft is evident for ships over 2000 Teu.

4.5. CONTAINERS

It was Morris Forgash, organizer of the world's largest freight forwarding organisation, United States Freight Company who proposed the geometry of ISO standards. He proposed the 8 ft. height by 8 ft. width dimensions with length variations of 10 ft, 20 ft, 30 ft and 40 ft. Heights of 8'6" were subsequently also accepted. It has already been mentioned in Section 4.1 that ISO standards were adopted in Moscow in 1967. Though the first container size standards were adopted as far back as 1961 by ASA, the developments were delayed mainly because of opposition from Sealand (8' x 8' x 35'), Matson's (8' x 8' x 24') and Grace Lines (non standard corner castings). This opposition resulted in a law under which Congress ordered equal treatment in the use of all container sizes (7).

Besides the ISO standards it has been recommended that shipowners must have these additional standards for mutual benefit (146).

a) Stricter inside dimensions
b) Uniformity of door openings (as large as possible)
c) Roof openings for open top containers
d) Uniformity in stacking loads
TABLE 4.8. Main characteristics of container ships. (Compiled from (14) and Lloyd's Register 81 of ships) over 500 TEU as on November 1, 1980.

<table>
<thead>
<tr>
<th>Size TEU</th>
<th>Numbers</th>
<th>Cargo Capacity in TEU</th>
<th>Cargo Capacity in Dead Weight tons</th>
<th>Length BP m.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Purpose Built</td>
<td>Converted</td>
<td>Total</td>
<td>Purpose Built</td>
</tr>
<tr>
<td>1. 500-599</td>
<td>18</td>
<td>16</td>
<td>34</td>
<td>9884</td>
</tr>
<tr>
<td>2. 600-799</td>
<td>35</td>
<td>24</td>
<td>59</td>
<td>24915</td>
</tr>
<tr>
<td>3. 800-999</td>
<td>46</td>
<td>24</td>
<td>70</td>
<td>39053</td>
</tr>
<tr>
<td>4. 1000-1199</td>
<td>54</td>
<td>37</td>
<td>91</td>
<td>60126</td>
</tr>
<tr>
<td>5. 1200-1399</td>
<td>40</td>
<td>7</td>
<td>47</td>
<td>50991</td>
</tr>
<tr>
<td>6. 1400-1599</td>
<td>61</td>
<td>-</td>
<td>61</td>
<td>90546</td>
</tr>
<tr>
<td>7. 1600-1799</td>
<td>49</td>
<td>-</td>
<td>49</td>
<td>81931</td>
</tr>
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<td>8. 1800-1999</td>
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<td>-</td>
<td>6</td>
<td>12296</td>
</tr>
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<td>10. 2200-2399</td>
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<td>-</td>
<td>6</td>
<td>13776</td>
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<td>-</td>
<td>11</td>
<td>27402</td>
</tr>
<tr>
<td>12. 2600-2799</td>
<td>9</td>
<td>-</td>
<td>9</td>
<td>24450</td>
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<tr>
<td>13. 2800-2999</td>
<td>6</td>
<td>-</td>
<td>6</td>
<td>17118</td>
</tr>
<tr>
<td>14. 3000</td>
<td>4</td>
<td>-</td>
<td>4</td>
<td>12064</td>
</tr>
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</table>

Contd.
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<tr>
<th>Size TEU</th>
<th>Speed in Knots</th>
<th>Shaft horse power</th>
<th>Draft m.</th>
<th>Depth m.</th>
<th>Breadth m.</th>
</tr>
</thead>
<tbody>
<tr>
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<td>14.64</td>
<td>8.262</td>
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<td>8,587</td>
<td>8,587</td>
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<td>7.20</td>
<td>11,421</td>
<td>12,000</td>
<td>30,400</td>
</tr>
<tr>
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<td>17.45</td>
<td>11,421</td>
<td>12,000</td>
<td>30,400</td>
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<td>16.69</td>
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<td>1,400–1,599</td>
<td>19.51</td>
<td>9.50</td>
<td>9,675</td>
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<td>30,000</td>
</tr>
<tr>
<td>1,600–1,799</td>
<td>19.53</td>
<td>9.675</td>
<td>11,773</td>
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<td>30,000</td>
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<td>11,773</td>
<td>10,583</td>
<td>30,000</td>
</tr>
<tr>
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<td>19.53</td>
<td>9.675</td>
<td>11,773</td>
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<td>30,000</td>
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<td>19.53</td>
<td>9.675</td>
<td>11,773</td>
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<td>19.53</td>
<td>9.675</td>
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<td>2,600–2,799</td>
<td>19.53</td>
<td>9.675</td>
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<td>2,800–2,999</td>
<td>19.53</td>
<td>9.675</td>
<td>11,773</td>
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<tr>
<td>3,000</td>
<td>19.53</td>
<td>9.675</td>
<td>11,773</td>
<td>10,583</td>
<td>30,000</td>
</tr>
</tbody>
</table>

TABLE 4.8 (Contd.)
e) Maximum tare weights to achieve a uniform payload  
f) Standard cargo lashing points; and  
g) Removable door headers for open top containers.

Since 1972 container vessels have been in service with cell guides capable of 9 high stacking. ISO has not changed the test procedure and requirement is still only for 6 high stacking. Of course one can recalculate 9 high stacking test loads based on 6 high figures, and thus be on the safe side. However other aspects should also be taken into consideration such as (a) ships with 9 high cells should have an acceleration factor less than 1.8g.  
(b) In the forward section where the bigger acceleration takes place, the hull shape often allows only 7 high or possibly 8 high stacking.  
(c) Fully loaded 40' containers up to maximum rating of 30 tons are seldom used.  
(d) It is unlikely that all containers stacked 9 high in one cell will all lie packed to the maximum weight.  
(e) To help stability, heavy containers are generally stowed at the bottom of the stack.

Table 4.9 outlines the various possible concepts in use or proposed for securing containers on deck.

The world's container population increased from some 450,000 Teu in 1970 to some 3,100,000 Teu in 1980 (31).

Containership productivity in the use of container boxes and the container productivity in terms of the amount of cargo carried per annum in a box can be analysed from the available data on the number of boxes in Teu, trade figures in tons and the available slots in the container fleet (31).

The container ship productivity development as shown in Fig. 4.11 is derived by dividing the available trade by the number of Teu's per slot/annum. It shows that Teu's/slot/annum increased fairly consistently till 1973 when due to the oil crisis there was a slump in the trade and therefore Teu's/slot/annum fell. There was growth in
TABLE 4.9. Various possible concepts, already in use or proposed for securing containers on deck (28).

- **Conventional Containers**
  - Containers mostly stowed under deck
    - Normal hatch coaming
    - Normal depth
  - Deck stowage: Max. 4 tiers containers on top of hatch covers
  - Several lashing systems

- **Containers with sophisticated stowage system for containers on deck**
  - Containers mostly stowed under deck
    - Normal hatch coaming
    - Raised hatch coaming
    - Low depth
  - Deck stowage: max. 2 tiers containers on top of hatch covers
  - Deck stowage several tiers of containers alongside the hatch coaming in cellular guides
    - Twist lock lashing system
    - Horizontal movable cellular guides
    - Vertical lifting off frame led by buttress arranged on deck
  - Stable cellular guides arranged on top of piggy back hatch covers
  - Stable cellular guides on deck with adapted hatch covers
  - Special pontoon hatch covers
  - Piggy back hatch covers
  - Folding hatch covers

- **Hybrid container ships**
  - Containers only stowed on deck
    - Low depth, no hatch openings, no cargo under deck
    - Deck stowage max. 4 tiers containers without cellular guides
  - Deck stowage more than 2 tiers of, in stable stowage scaffolding on deck
  - Movable stowage scaffolding with conventional pontoon hatch covers
  - Stable cellular guides arranged on top of piggy back hatch covers
  - Stable cellular guides on deck with adapted hatch covers
  - Special pontoon hatch covers
  - Piggy back hatch covers
  - Folding hatch covers

- **Mixed systems with containers on deck only, no hatches**
  - Normal depth
  - Deck stowage max. 4 tiers containers without cellular guides

- **Other cargo stowage under deck:**
  - Ro-Ro, barges, Liquid cargo.
  - Deck stowage max. 4 tiers containers without cellular guides
  - Deck stowage more than 2 tiers containers in stable cellular guides
  - Several lashing systems

- **Several lashing systems**
1975-1978 and is on the decline since then. A similar analysis performed for the productivity of the individual container, Fig. 4.12, shows that after a fairly consistent period of 50 tons/box/annum level over 1970-74, output per Teu increased to this same level over 1976-78 after falling dramatically in 1975. The container productivity, Fig. 4.12, in 1980 was 39 tons/box/annum which may fall to 37 tons/box/annum in 1983 and level at 39 tons/box/annum in 1985(31). Similarly containership productivity, Fig. 4.11, was 159 t/slot/annum in 1980 and will fall to 149 to 151 t/slot/annum in the period 1981-85(31).

It is evident that there is an excess number of container boxes and at current level of trade growth this excess container box capacity will not be absorbed by 1985 or experience may show that substantial excess number of containers continue to be a feature of the container traffic.
Fig. 4.11. Container ship productivity development (31). Fig. 4.12. Container productivity development (31).
CHAPTER 5
ESTIMATING THE MAIN PARTICULARS

5.0 INTRODUCTION
5.1 CONTAINER STACKING
5.2 BREADTH MOULDED
5.3 DEPTH
5.4 LENGTH BP
5.5 DRAFT
5.6 BLOCK COEFFICIENT
5.7 STRUCTURAL DESIGN CONSIDERATION
5.8 GROSS AND NET TONNAGE
5.9 FREEBOARD TYPE-B
5.0 INTRODUCTION

This chapter considers the main particulars of container ships. It indicates how the dimensions must reflect integer multiples of container sizes with due regard for clearance and structure. Main dimensions of container ships are compared with existing formulae and the approach of the program indicated. The main dimensions suit the number and stowage of containers with the usual design allowances to ensure that structure and seakeeping requirements will not pose serious problems.

Some general observations may be made concerning the main dimensions of ships which are usually taken to be Length L, Breadth B, Depth D and Draft T. Since the surface of a ship represents cost and its volume earning power, the simplest possible analysis would indicate that all ships would be spheres or cubes with least surface and maximum volume. Actual ship shapes are distortions from this simple concept imposed by the demands of propulsion, stability, strength, seakeeping, deck cargo and indeed harbours and canals. Generally particular influences predominate on each main dimension while others are secondary.

The following are listed in (35) B = f(L); D = f(B); T = f(D); D = f(L); T = f(L) and T = f(B) and are now considered for container ships.

(a) B = f(L) is shown in Fig. 5.1. A small L/B ratio leads to a lower capital cost (13, 35) but is detrimental to course keeping, and propulsive efficiency and also powering if residuary resistance predominates (11)(35).

In the program L/B is kept between 6 and 9. First generation container ships built in 1968 had L/B ratios about 6.3; The second generation built in 1970 had these ratios about 7.1 and they ran to about 8.5 as speeds increased faster than size. The fuel crisis reduced the value in third generation ships to about 6.3 similar to those of the first generation; although by 1979 values of 7.7 were recorded. Table 4.3 describes the different generations, although increasing numbers and special cases have blurred distinctions.
Fig. 5.1. **LENGTH BP VERSUS BREADTH MOULDED**

REF: CONT'L INT'LY BOOK 181, LUDY DS REGISTER (14, 34).

**LENGTH/BREADTH RAT.**

```
+ + + +
```

**BREADTH MLD. IN METRES**

Panama Canal Beam

```
L/B = 6.0
L/B = 6.32
L/B = 7.0
L/B = 7.75
L/B = 8.5
L/B = 9.0
```

**St. Lawrence Seaway**

```
Panama Canal
```

**LENGTH BP IN METRES**

110 130 150 170 190 210 230 250 270 290
(b) \( D = f(B) \). This is shown in Fig. 5.2. This relationship influences stability as \( KM \) is a function of breadth and \( KG \) is influenced by Depth. In containerships where much cargo is on deck, Depth is not an over-riding influence on \( KG \) which is largely influenced by deck containers and ballast carried. However Beam is influenced by the Panama Canal and \( B/D \) is usually close to 1.65.

(c) \( T = f(D) \). This is shown in Fig. 5.3, and shows that most containerships have a working design draft well below the maximum permitted by geometry as defined in the freeboard calculation.

(d) \( D = f(L) \). This relationship is shown in Fig. 5.4. The \( L/D \) ratio has an upper limit to avoid undue flexibility, and in the program \( L/D \) is restricted to be between 10 and 14.5. There is an attraction in limiting the steel weight associated with Depth and Langenberg (36) gives a net saving of 4% on hull steel weight with a trunk type of ship which has a depth at side less than the conventional double skin construction.

(e) \( T = f(L) \). This relationship is shown in Fig. 5.5. For good seakeeping \( T/L \) should exceed 0.045 to avoid slamming in a seaway (27). Most containerships meet this requirement. Seakeeping considerations are discussed in Chapter 13.

(f) \( T = f(B) \). This relationship is shown in Fig. 5.6. Most container ships have \( B/T \) lower than 3.15 and the program has limits of 2.25 and 3.75. Panama Canal restrictions are important. Some important canal and river draft restrictions are listed below.
Fig. 5.4. LENGTH DP VERSUS DEPTH MOULDED
REF. CONT. INTL. YR. BOOK-81, LLOYDS REGISTER (14, 34).

LENGTH/DEPTH
RATIO

---

DEPTH MLD IN METRES

---

LENGTH DP IN METRES

---

L/0 = 10

---

L/0 = 14.5

---

L/0 = 15

---

Panama Canal Locks

---

Loe = 289

---
Fig. 5.5. LENGTH BP. VERSUS DRAFT SCANTLING
REF. CONT. INTL. YR. BOOK-81, LLOYDS REGISTER (14, 34).

DRAFT SCANTLING IN METRES

T/L RATIO

Panama Canal Draft Seasonal
Panama Canal Locks Limiting
Panama Canal Locks

LENGTH BP. IN METRES
Fig. 5.6. BREADTH MLD. VS SCANTLING DRAFT
REF. CONT. INTL. YR. BOOK-81, LLOYDS REGISTER (14, 34).

SCANTLING DRAFT IN METRES

BREADTH MLD. IN METRES

B/T = 2.25
B/T = 3.75

BREADTH/DRAFT RATIO
+++
5.1 Container Stacking

The vertical cell type container ships have containers stacked in vertical cells formed by angle corner guides. The container cells are arranged so that the long dimensions of the containers are fore and aft; principally because this stowage is better suited to handling with a gantry crane over the side and it is also easier to integrate with the ship structure. Cell guides provide an efficient lateral support at the four corners of the container against transverse and longitudinal movement caused by dynamic forces. The deck containers can be stacked up to 4 high and are lashed to the deck or hatch cover. For the containers stacked in holds it is important that the tolerances and clearances necessary for the loading, unloading, stacking and inspection be taken into consideration.

Table 5.1 summarises the various tolerances and clearances which have been suggested in the literature. At the preliminary design stage container/container clearances is what a designer is concerned with. A value of 230 mm is chosen as indicative of an average value, since hold and/ container clearances are much less (see Fig. 5.8). In the program the user inputs the container dimensions only, as

*Suez Canal  Panama Canal  Kiel Canal  Amsterdam Canal

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
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<td>draft in m.</td>
<td>11.6*</td>
<td>11.7</td>
<td>9.0</td>
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<tr>
<td>Welland Canal</td>
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<tr>
<td>Schelde Antwerp</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>St. Lawrence Seaway</td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>

<p>| | | |</p>
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<th></th>
</tr>
</thead>
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<td>draft in m.</td>
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<td>11.6</td>
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</table>

*Recently increased.
TABLE 5.1. Container/cell tolerances and clearances (All dimensions in millimetres).

<table>
<thead>
<tr>
<th>Container Size</th>
<th>Container Tolerance</th>
<th>Container/cell guide</th>
<th>Cell guide tolerance</th>
<th>Container/container clearance</th>
</tr>
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<tr>
<td></td>
<td>longl. Trans.</td>
<td>longl. transverse</td>
<td>longl. trans.</td>
<td>Flip/Flop Fixed even peaks High low peaks</td>
</tr>
<tr>
<td>20'</td>
<td>6055 +3 -3</td>
<td>2435 +3 -2</td>
<td>44 28 28 18</td>
<td>± 10 ± 5</td>
</tr>
<tr>
<td>20'</td>
<td>6055 +3 -3</td>
<td>2435 +3 -2</td>
<td>35 32 25 22</td>
<td>± 5 ± 4</td>
</tr>
<tr>
<td>ISO 20'</td>
<td>6058 +0 -6</td>
<td>2438 +0 -5</td>
<td>13</td>
<td>- -</td>
</tr>
<tr>
<td>40'</td>
<td>12190 +2 -8</td>
<td>2435 +3 -2</td>
<td>42 32 25 22</td>
<td>± 5 ± 4</td>
</tr>
<tr>
<td>ISO 40'</td>
<td>12192 +0 -10</td>
<td>2438 +0 -5</td>
<td>13</td>
<td>- -</td>
</tr>
</tbody>
</table>

(Subject to latest revisions.)
shown in Fig. 5.7, the values of container length (CL), width (CW) and the container height (CH). A 20' x 8' x 8' ISO container is assumed in the program. If 8'6" high containers are to be used, the user can change the value of CH in the program.

5.2. Breadth

The breadth of a container ship is mainly determined by the following requirements:

(a) Container capacity
(b) External constraints (e.g., width of the locks, e.g., Panama Canal and the St. Lawrence Seaway, outreach of container cranes etc.)
(c) Hatch division and systematic container grid for ease in cargo handling
(d) Stability
(e) Strength.

Given the number of rows of containers athwartship, beam is a function of container width plus tolerances and clearances between container and cells plus the 'lead in' or 'gather' i.e. the distance that the cell guide splay out at the top to catch the downcoming containers plus sufficient deck width outside the hatches for required strength and stability. The container hold dimensions are thus decided from geometric considerations. The deck width on either side is however governed by factor (b), (d) and (e). Since beam largely governs the value of KM and hence the stability, adequate beam must be provided.

Container ships have very wide hatch openings, sometimes in excess of 80%, see Table 5.2. This open type of ships has introduced two basic problems to the structural design of ships; firstly the open type section creates difficulties in providing sufficient cross sectional material to satisfy the longitudinal strength, and secondly, the geometry of the cross section lacks torsional rigidity. For ships with 9-10 rows of containers, for strength and stability reasons Hoppe (13) for third generation ships, recommends a deck width of 2.2m to 3.5 m. Similarly Meek (19) took 20% of the beam for the first generation ships.
Fig. 5.7. Container dimensions, tolerances (All dimensions in mm.)

20' x 8' x 8'

6055 + 3 (CL)
6090
12224
12190 + 2 (CL)

40' x 8' x 8'

2435 + 3 (CW)
2468
2668
TABLE 5.2. Container stacking characteristics Athwartship. (From various shipping and shipbuilding Journals.)

<table>
<thead>
<tr>
<th>No.</th>
<th>Ship's Name</th>
<th>Breadth (B) m.</th>
<th>Hold Width (HW) m.</th>
<th>Deck Width (DW) m.</th>
<th>Deck width % age</th>
<th>Rows</th>
<th>Breadth Rows m.</th>
<th>Hold Width Rows m.</th>
<th>Container/container clearanse athwartship mm.</th>
<th>No. of Girders</th>
<th>Width of girder mm.</th>
</tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
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<td>2</td>
<td>A</td>
<td>32.15</td>
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<td>2.828</td>
<td>390</td>
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<td>4</td>
<td>C</td>
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<td>3.522</td>
<td>2.743</td>
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<td>D</td>
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<td>406</td>
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<td>No.</td>
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<td>Hold Width (HW) m.</td>
<td>Deck Width (DW) m.</td>
<td>Deck width B % age</td>
<td>Rows</td>
<td>Breadth Rows m.</td>
<td>Hold Width Rows m.</td>
<td>Container/ container clearance athwartships mm.</td>
<td>No. of Girders</td>
<td>Width of girder mm.</td>
</tr>
<tr>
<td>-----</td>
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<td>12</td>
<td>Manchester Vigour</td>
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<tr>
<td>No.</td>
<td>Ship's Name</td>
<td>Deck width (B)</td>
<td>Hold width (Ho)</td>
<td>Breadth (B)</td>
<td>% age</td>
<td>Deck width (%)</td>
<td>Hold width (%)</td>
<td>No. of girders</td>
<td>Width of girders mm.</td>
<td>Container clearance athwartships mm.</td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>------------------</td>
<td>----------------</td>
<td>----------------</td>
<td>-------------</td>
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<tr>
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<td>26.00</td>
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<td>Seelandia</td>
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<td>Elbe Express</td>
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<td>12.75</td>
<td>1</td>
<td>2.715</td>
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<td>Manchester Challenge</td>
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<td>2.75</td>
<td>12.75</td>
<td>1</td>
<td>2.715</td>
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<td>30</td>
<td>CP Voyager</td>
<td>26.00</td>
<td>32.20</td>
<td>20.24</td>
<td>8</td>
<td>2.75</td>
<td>12.75</td>
<td>1</td>
<td>2.715</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
To provide adequate deck stringer width for structural reasons the minimum value was assumed to be 14% of the beam, and the maximum 20% of the beam.

Three methods were available to estimate the minimum beam of container ships, these are described briefly together with the approach adopted in the program.

**Method 1.**

Let Fig. 5.8 represent the geometry of a container ship. Then the breadth $B$ (20) is given by

$$B = 2W + 2C_1 + n_1d + (n-2)C + nbo$$  \hspace{1cm} \text{Eq. 5.1}

$W =$ width of the deck stringer, which varies from 2.25 m to 2.98 m for a Panamax beam of 32.26 m;

$C_1 =$ clearance between the inner hull to the first cell guide

$n_1 =$ number of girders

$d =$ overall width of a deck girder

$n =$ number of container rows

$C =$ clearance between adjacent cell guides

$bo =$ width of the container + thickness of the cell guides

$= (2460 + 2t) \text{mm}.$

$t =$ thickness of the cell guides.

The value of $C$ will depend on the type of precentring device adopted as shown in Fig. 5.9.

**Method 2.**

Chryssostomidis (37) calculates the minimum breadth as follows:

Hold width $= nxbo + nC + n_1d$  \hspace{1cm} \text{Eq. 5.2}

where $C =$ 152 mm for shipboard cranes

$= 228 \text{ mm for shore based cranes}$

$d =$ width of the deck girder is taken as 305 mm

$n_1 =$ number of girders, assumed to be one if number of rows is even and two if it is odd

The breadth of the ship is then given by

$$B = \text{Hold width} + W$$
Fig. 5.8. Midship container arrangement showing dimensions & clearances (20).

- \( W = 2250-2980 \) for \( n = 10 \)
- \( b = 2488 \) mm
- \( c = 120 \) mm
- \( c = 80 \) flip flop
- \( n = 2 \)
- \( d = 600-800 \) mm

- \( C_1 = 110-180 \) mm
- \( C_1 < 110 \) with \( C_1 = 50 \) mm has been applied

- \( n = \text{no. of containers} \)

- \( \text{high low peak} \)
Fig. 5.9. Container clearances for different types of precentring arrangements (20).

(a) FLIP-FLOP TYPE INLETS

(b) FIXED EVEN PEAKS

(c) HIGH LOW PEAKS
where \( W = 3.962 \text{ m} \) for 7 rows of containers
\[ = 4.572 \text{ m} \] for 8 rows of containers
\[ = 5.182 \text{ m} \] for 9 rows of containers

Method 3.

Nakamura (24) gives the following relationship for calculating the breadth:

\[
B = \text{Rows} \times CW + (n_H - 1)b_1 + 2 \times \text{Clear } W_1 \times n_H + (\text{rows} - n_H) \times \text{Clear } W_2
\]  
Eq. 5.3

Rows = no. of container rows athwartship
\( CW = \) width of the containers taken as 2461 mm
\( n_H = \) number of rows of hatchways 2 or 3
\( b_1 = \) distance between hatchways = 650 mm
Clear \( W_1 \) = clearance between side structure and container = \( \frac{455}{2} \) mm
Clear \( W_2 \) = clearance between adjacent cell guides = 130 mm

In the program the minimum and the maximum breadth is calculated as follows:

Total width of the block of containers (BLOCK W) is given by

\[
\text{BLOCK } W = \text{CONTW} + \text{CLEARW} + \text{CLEARF}
\]  
Eq. 5.4

\( \text{CONTW} = \) total space taken by containers alone = number of rows of containers (ROWS) \( \times CW \)
where \( CW = \) width of one container = 2438 mm

The total clearance between containers is CLEARW and is given by

\[
\text{CLEARW} = \text{CLEAR 1} \times \text{ROWS}, \text{where clearance between each container given by CLEAR 1 is assumed to be 230 mm.}
\]

CLEARF is the clearance for the width of the flanges. If there are even numbers of rows of containers, a single centre line hatch girder is assumed and if there are odd numbers of rows of containers then two longitudinal hatch girders are placed symmetrically on either side of the centre line. It is also possible to have asymmetrically placed girders on either side of the centre line (20) of the ship. The usual space required for such a girder is 600-
800 mm (20). Then the minimum breadth is given by

\[ B_{\text{MIN}} = \frac{\text{BLOCKW}}{0.80} \text{ m} \quad \text{Eq. 5.5} \]

and the maximum breadth is given by

\[ B_{\text{MAX}} = \frac{\text{BLOCKW}}{0.80} \text{ m} \quad \text{Eq. 5.6} \]

or \( B_{\text{MAX}} = 32.26 \text{ m} \) whichever is less.

As shown in Table 5.2 the width of the deck at side can vary from 14.77% of the breadth to 24.21% of the breadth for ships with 8 rows of containers (ship no. 16 & 20). Though these were the extreme limits, such a large variation was kept in the program, because at the preliminary stage it is best to explore the extreme limits, without imposing unnecessary constraints.

A comparative evaluation with the other methods, see Table 5.3, indicates that the minimum and the maximum breadth calculated by the program lies in between the values calculated by method 2 and 3.

5.3. Depth

The depth at side to uppermost continuous deck of a containership is a function of the following five items:

(a) Double bottom height (DBHM)

Previous containership studies (37) have either taken the double bottom as a function of the number of tiers of containers under deck or as required by the classification rules (38) to ensure adequate strength. Chryssostomidis (37) takes the double bottom height as 1372 mm for 8 tiers and 1220 mm for 7 tiers in hold, and the minimum depth of the centre girder (minimum double bottom height) is given by

\[ \text{DBHM} = \frac{1000 \times B}{36} + 205\sqrt{T} \text{ in mm.} \]

Most ships however have height of the double bottom in excess of those required by strength considerations alone, since adequate space is to be provided for the fuel, freshwater and the ballast. Double bottom height of some containerships are given in Table 5.4. To provide adequate space as mentioned above the following equation was used
<table>
<thead>
<tr>
<th>Item</th>
<th>Method</th>
<th>Rows</th>
<th>5</th>
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<td></td>
<td>Formulas</td>
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<td>Container space</td>
<td>bo</td>
<td>2488</td>
<td>2438</td>
<td>2461</td>
<td>2438</td>
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<td>Total cont. space</td>
<td>nbo</td>
<td>12440</td>
<td>12190</td>
<td>12305</td>
<td>12190</td>
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<tr>
<td>Clearance between cell-cont.</td>
<td>(n-2)c</td>
<td>240/660</td>
<td>152-</td>
<td>540</td>
<td>230mm</td>
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<tr>
<td>Clearance container hold</td>
<td>2C1</td>
<td>220/360</td>
<td>228</td>
<td>455</td>
<td>220/360</td>
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<tr>
<td>Total clearance for cell guides</td>
<td>Min/Max (3)+(4)</td>
<td>460/1020</td>
<td>762/1143</td>
<td>995</td>
<td>1150</td>
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<tr>
<td>Width of girder</td>
<td>d</td>
<td>600/800</td>
<td>305</td>
<td>650</td>
<td>305</td>
</tr>
<tr>
<td>No. of girders</td>
<td>n₁</td>
<td>2</td>
<td>2</td>
<td>2</td>
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</tr>
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</table>

TABLE 5.3. Estimation of breadth by different methods (all dimensions in millimetres).
TABLE 5.3. (Contd.)

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<th>Rows Method</th>
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<th>1</th>
<th>2</th>
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<td>Clearance for girders</td>
<td>n₁d</td>
<td>1200/1600</td>
<td>610</td>
<td>1300</td>
<td>610</td>
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<td>650</td>
<td>305</td>
<td>1200/1600</td>
<td>610</td>
<td>1300</td>
<td>610</td>
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<tr>
<td>Overall min. hatch width</td>
<td>(2) + (5) + (8)</td>
<td>13500</td>
<td>13562</td>
<td>14600</td>
<td>13950</td>
<td>16068</td>
<td>15847</td>
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<td>19882</td>
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<td>Width of side tk. min.</td>
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<td>Width of the side tank</td>
<td>WAVG / WMAX</td>
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<td>3488</td>
<td>3339/4076</td>
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<td>8 min.</td>
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<td>BAVG / B MAX</td>
<td>16798/17429</td>
<td>17438</td>
<td>19645/20381</td>
<td>20391</td>
<td>23240/24095</td>
<td>24108</td>
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* t = thickness of the cell guide

\[ c = 80 - 220 \text{ mm} \]
\[ c₁ = 110-180 \text{ mm} \]
\[ d = 600 - 800 \]
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<td>2438</td>
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<td>560/1540</td>
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<td>1260</td>
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<td>220/360</td>
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<td>455</td>
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<tr>
<td>Total clearance</td>
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<td>600/800</td>
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<tr>
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<td>1200/1600</td>
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<td>1300</td>
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<td>600/800</td>
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TABLE 5.4. Container stacking characteristics in tiers.

<table>
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<th>Ship no.</th>
<th>Depth (D) m.</th>
<th>Height of Double Bottom (DBHM) m.</th>
<th>D-DBHM Tiers m.</th>
<th>Tiers</th>
<th>Height of hatch coaming mm.</th>
<th>Plating Thickness mm</th>
<th>Camber mm</th>
<th>Clearance from underside of hatch cover to top of container mm.</th>
<th>Depth of hatch cover mm.</th>
<th>Depth Tiers mm.</th>
<th>Doublar Plating mm.</th>
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<td>D-DBHM m.</td>
<td>Tiers</td>
<td>D-DBHM Tiers m.</td>
<td>Height of hatch coaming mm.</td>
<td>Plating Thickness mm</td>
<td>Camber mm</td>
<td>Clearance from underside of hatch cover to top of container mm.</td>
<td>Depth of hatch cover mm.</td>
<td>Depth Tiers mm.</td>
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</tr>
</tbody>
</table>
DBHM = (0.15 x TIERB + 0.65) m \hspace{1cm} \text{Eq. 5.7}

where TIERB = tiers of containers in the hold which ranges from 5 to 9.

(b) Centre strake thickness (PLTHK)

The centre strake thickness is given by

\[ PLTHK = 0.52 + \left( \frac{L_B - 440}{1250} \right) + 0.08 \text{ inches, } L_B = \text{length in feet} \] (37)

or

\[ PLTHK = 0.00136(S + 660) \sqrt[4]{L_{Bp} \times T} \text{ mm} \] (38)

where \( S = \text{frame spacing in mm.} \)

Since the main dimensions are not known at this stage of the design the centre strake thickness is approximated by the following formula

\[ PLTHK = (1.25 x \text{TIERB} + 1.75)/1000.0 \text{ m} \hspace{1cm} \text{Eq. 5.8} \]

(c) Container blockheight (CBH)

\[ CBH = \text{TIERB} \times \text{CH} + \text{DTHK} + \text{CLEAR2} \hspace{1cm} \text{Eq. 5.9} \]

where \( \text{CH} = \text{container height in m. either 2.438 m. (8') or 2.591 m. (8' 6'').} \)

\( \text{DTHK} = \text{thickness of the doubler plate, 25 mm.} \)

\( \text{CLEAR2} = \text{clearance between the uppermost container tier below deck and the underside of the hatch cover. Table 5.4 gives some typical values for containerships. Chryssostomidis (37) and Nakamura (24) give a value of 100 mm. A value of 300 mm was taken in the program. It is possible to specify 8'6'' containers also by changing the value of CH.} \)

(d) Camber (CAMBER)

The deck chamber of containerships is assumed to increase linearly to its maximum value at the side of the hatch opening. In the program CAMBER = 0.075 m, which is also the value taken by Chryssostomidis (37). As shown in Table 5.4 some containerships have no camber or very high camber of 400 mm. A camber of 75 mm seems reasonable.

(e) Hatch coaming height (HATCHT)

The minimum hatch coaming height in position 1, i.e.
hatchways exposed on freeboard decks is 600 mm (38). Chryssostomidis (37) gives a value of 915 mm and Nakamura (24) 760 mm, though actual practice is to give large hatch coaming height, to reduce the depth of the ship, thereby reducing the steel weight (36) and also to stack as many containers below the deck as practicable. Table 5.4 indicates that hatch coaming height of 1000 mm is usual practice. As mentioned earlier in Section 5.2, the minimum value is adopted in the program together with a maximum value, and the most economic depth determined. Thus to calculate the minimum depth, hatch coaming height was taken as 1000 mm.

With the knowledge of the preceding 5 items, the minimum depth $D_{\text{min}}$ at side is given by

$$D_{\text{MIN}} = DBHM + PLTHK + CBH - CAMBER - HATCHT \quad \text{m} \quad \text{Eq. 5.10}$$

and the maximum depth is approximated by

$$D_{\text{MAX}} = D_{\text{MIN}} + 1.2 \quad \text{m} \quad \text{Eq. 5.11}$$

For a given number of tiers in hold, statistical analysis shows that the depth at side can vary by 1.2 m for $TIERB = 5$ to 9. This gives a variation in Depth of 2.569 m to $\frac{2.809}{TIERB}$. Table 5.4 indicates that for actual ships the extreme variation of $\text{Depth/TIERB}$ is 2.13 m (Ship no. 12) to 2.926 m (Ship no. 26) for $TIERB = 5$. The average variation is much less and the values adopted in the program are reasonable.

Two methods which were used in past studies to determine the depth are described briefly.

**Method 1.** Erichsen (39) gives the minimum depth as follows:

$$D > 8 \times TIERB + \left(\frac{L_{BP} - 500}{100}\right) \quad \text{ft}, \quad L_{BP} \text{ in ft}, \quad \text{Eq. 5.12}$$

where $TIERB = 5$ for $400 < CNT \leq 700$

$= 6$ for $700 < CNT \leq 1700$

$= 7$ for $CNT > 1700$

where $CNT = \text{total number of containers}$

$$D \leq 60 + \left(\frac{L_{BP} - 500}{100}\right) \quad \text{ft}, \quad L_{BP} \text{ in ft}.$$  

when $TIERB = 7$
Method 2.

Nakamura (24) gives the following equation for determining the depth

\[ D = CH \times TIERB + DBHM + CLEAR2 - HATCHT - CAMBER \text{ m} \quad \text{Eq. 5.13} \]

where \( DBHM = \frac{B}{16} \text{ in m.}; \) CLEAR2 = 0.100 m, HATCHT = 0.760 m, CAMBER = \( \frac{B}{2} \times \frac{45}{1000} \text{ m.} \)

A comparative evaluation with the above two methods is given in Table 5.5 together with that adopted in the program. This shows that the minimum and the maximum values calculated are reasonable.

5.4. Length BP

The length of the containership was subdivided into container hold length, machinery space length and fore and aft peak length. Each of these are considered in turn.

(a) Container hold length (BLOCKL)

The container hold length is composed of length of the container, manufacturer's tolerance on container length, clearance between container and cell guide, tolerance in cell guide construction, (Table 5.1), container lead-in (Fig. 5.9), structure to support cell guides and bulkheads and/or other transverse ship structure. Because the containers are supported at their corners only, the position of the ship's transverse strength members and transverse frame spacing are directly related to the container length. The same underlying reasoning applies to depth and breadth of the ship.

Table 5.6 shows the container stacking characteristics in bays. For a 20' container the minimum distance per bay varies from 6.748 m to a maximum of 7.979 m/bay. Buxton (15) gives a value of 1.5 - 2.5 m for clearance between adjacent bays. As shown in Table 5.6, total clearance/hold, will depend on the container size, mix of the containers (40' and 20'), number of bays of containers in each hold, type of container (e.g. Reefers require more space) and the location of the container (e.g. container in forward holds require more space), which explains the large variation in the hold clearances.
TABLE 5.5. Estimation of depth by different methods. (All dimensions in mm.).

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<tr>
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<th>Symbol</th>
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<td><em>2.)</em> 2</td>
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<td>1</td>
<td>2</td>
<td><em>2.)</em> 3</td>
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<td>2591</td>
<td>2438</td>
<td>2438/2591</td>
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<td>12955</td>
<td>121900</td>
<td>14628/15546</td>
<td>15546</td>
<td>14630</td>
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<td>1400</td>
<td>1400</td>
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<td>1550</td>
<td>1500</td>
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<td>9.25</td>
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<td></td>
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<td>CLEAR2</td>
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<td>100/300</td>
<td>100/300</td>
<td>100</td>
<td>100/300</td>
<td>100/300</td>
</tr>
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<td>14488/14688</td>
<td>13723/13923</td>
<td>17456</td>
<td>17230/17430</td>
<td>16315/16515</td>
</tr>
<tr>
<td>height</td>
<td>(4)+(5)+</td>
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<td>760</td>
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<td>1000</td>
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<td>652</td>
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TABLE 5.5. (Contd.).

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<th>Symbol</th>
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<td>-</td>
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<td>13848/14048</td>
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Note:

*1. For methods 1 & 2 following ships were chosen.

*2. Program values assuming 8'6" containers.

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<th>DBHM(m)</th>
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TABLE 5.5. (Contd).

Note:
1) For Method 2. The following ships were chosen.

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<th>DBHM</th>
<th>Ship's Name</th>
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</thead>
<tbody>
<tr>
<td>8</td>
<td>236.00</td>
<td>32.08</td>
<td>20.725</td>
<td>2.000</td>
<td>Remuera</td>
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<td>32.20</td>
<td>23.90</td>
<td>1.70</td>
<td>Selandia</td>
</tr>
</tbody>
</table>

82
### TABLE 5.6. Container stacking characteristics in Bays.

<table>
<thead>
<tr>
<th>Length of Container hold m.</th>
<th>Container size ft.</th>
<th>No. of bays</th>
<th>Per 20' container bay space m.</th>
<th>Clearance per 20' container bay m.</th>
<th>Longitudinal Clearance (in metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Number of container bays/hold</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>174.10</td>
<td>35 x 8 x 8.5</td>
<td>15</td>
<td>-</td>
<td>360</td>
</tr>
<tr>
<td>2</td>
<td>174.10</td>
<td>35 x 8 x 8.5</td>
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<td>-</td>
<td>-</td>
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<td>6.890</td>
<td>-</td>
</tr>
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<td>7.086</td>
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</tr>
<tr>
<td>5</td>
<td>169.42</td>
<td>40 x 8 x 8.5</td>
<td>12</td>
<td>7.059</td>
<td>1.896</td>
</tr>
<tr>
<td>6</td>
<td>140.90</td>
<td>20 x 8 x 8</td>
<td>18</td>
<td>7.827</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>118.872</td>
<td>24 x 8 x 8.5</td>
<td>13</td>
<td>-</td>
<td>-</td>
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<td>7.44</td>
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<tr>
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<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>11</td>
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<td>18/5</td>
<td>7.925</td>
<td>1.828</td>
</tr>
<tr>
<td>12</td>
<td>74.23</td>
<td>20 x 8 x 8</td>
<td>11</td>
<td>6.748</td>
<td>0.652</td>
</tr>
</tbody>
</table>

Note: The table represents the stacking characteristics of containers in different bays, with columns for the number of containers and their dimensions, as well as the clearance per bay. The longitudinal clearance is listed for different combinations of container bays, with columns for minimum and maximum values.
TABLE 5.6. Container stacking characteristics in Bays. (Contd.)

<table>
<thead>
<tr>
<th>Length of Container hold m.</th>
<th>Container size ft.</th>
<th>No. of bays</th>
<th>Per 20' container bay space m.</th>
<th>Clearance per 20' container bay m.</th>
<th>Longitudinal Clearance (in metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Number of container bays/hold</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
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<tr>
<td>13</td>
<td>189.42</td>
<td>20 x 8 x 8</td>
<td>26</td>
<td>7.285</td>
<td>1.189</td>
</tr>
<tr>
<td>14</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>181.50</td>
<td>40 x 8 x 8</td>
<td>13</td>
<td>7.03</td>
<td>0.934</td>
</tr>
<tr>
<td>16</td>
<td>139.953</td>
<td>20 x 8 x 8</td>
<td>17/1</td>
<td>7.366</td>
<td>1.269</td>
</tr>
<tr>
<td>17</td>
<td>151.98</td>
<td>20</td>
<td>20</td>
<td>7.599</td>
<td>1.503</td>
</tr>
<tr>
<td>18</td>
<td>143.10</td>
<td>20 x 8 x 8 R</td>
<td>19</td>
<td>7.606</td>
<td>1.510</td>
</tr>
<tr>
<td>19</td>
<td>157.23</td>
<td>20 x 8 x 8</td>
<td>11/6</td>
<td>6.836</td>
<td>0.739</td>
</tr>
<tr>
<td>20</td>
<td>118.872</td>
<td>24 x 8 x 8</td>
<td>13</td>
<td>-</td>
<td>-</td>
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<tr>
<td>21</td>
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<td>16</td>
<td>7.044</td>
<td>0.948</td>
</tr>
<tr>
<td>22</td>
<td>189.59</td>
<td>20</td>
<td>26</td>
<td>7.292</td>
<td>1.196</td>
</tr>
<tr>
<td>23</td>
<td>140.5</td>
<td>40 x 8 x 8</td>
<td>10</td>
<td>7.276</td>
<td>1.180</td>
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</table>
TABLE 5.6. Container stacking characteristics in Bays. (Contd.)

<table>
<thead>
<tr>
<th>Length of Container hold m.</th>
<th>Container size ft.</th>
<th>No. of bays</th>
<th>Per 20' container bay space m.</th>
<th>Clearance per 20' container bay m.</th>
<th>Longitudinal Clearance (in metres)</th>
<th>Number of container bays/hold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>40 x 8 x 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1)20</td>
</tr>
<tr>
<td>25</td>
<td>199.47</td>
<td>20 x 8 x 8</td>
<td>17/5</td>
<td>7.979</td>
<td>1.883</td>
<td>2.448</td>
</tr>
<tr>
<td></td>
<td>40 x 8 x 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(2)20</td>
</tr>
<tr>
<td>26</td>
<td>124.00</td>
<td>20 x 8 x 8</td>
<td>18</td>
<td>6.888</td>
<td>0.792</td>
<td>1.808</td>
</tr>
<tr>
<td>27</td>
<td>147.00</td>
<td>20 x 8 x 8</td>
<td>19</td>
<td>7.737</td>
<td>1.641</td>
<td>0.904</td>
</tr>
<tr>
<td>28</td>
<td>109.86</td>
<td>20 x 8 x 8.5</td>
<td>5/5</td>
<td>7.324</td>
<td>1.228</td>
<td>2.451</td>
</tr>
<tr>
<td></td>
<td>40 x 8 x 8.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(2)20</td>
</tr>
<tr>
<td>29</td>
<td>103.472</td>
<td>20 x 8 x 8</td>
<td>14</td>
<td>7.391</td>
<td>1.295</td>
<td>2.888</td>
</tr>
<tr>
<td>30</td>
<td>94.85</td>
<td>20 x 8 x 8</td>
<td>8/3</td>
<td>6.775</td>
<td>0.679</td>
<td>2.438</td>
</tr>
</tbody>
</table>

NOTE: R = Reefer containers.
To take into account the different mixes of container sizes that can be stacked in a hold and also the variation in size of the hold (e.g. 2 bays or 3 bays of container/hold) the following method was adopted.

The procedure described here is done by subroutine subprogram DESIGN and the procedure is similar to one given by Chryssostomidis (37).

(i) Determine the total number of containers amidship in one bay from the number of rows of containers athwartship and tiers of containers below deck.

\[ CNPR = \text{ROWS} \times \text{TIERB} \quad \text{container/bay} \quad \text{Eq. 5.14} \]

(ii) The hold capacity of the containerships is approximated by Eq. 13.12 and the deck capacity by Eq. 13.11 (Section 13.2.1).

(iii) Since there is a loss of cubic space due to the ship shape form, a certain value of shape coefficient (CSHAPE) is assumed, (Section 13.2.2).

(iv) Then CNRI, the number of containers that can be accommodated in N-bays (BAYS) if the shape coefficient is 1, is given by

\[ CNRI = \text{BAYS} \times \text{CNPR} \]

and \[ CNRA = \text{CNRI} \times \text{CSHAPE} \quad \text{Eq. 5.15} \]

The number of BAYS is incremented in steps of 1 until the integer value of CNRA is equal to the hold capacity (CNTHLD) estimated in step(ii).

(v) The number of bays/hold (NCLPH) which is input by the user, is then used to determine the hold length. The user can input 1 bay/hold to 4 bays/hold which gives for a 20' container, the largest possible hold dimensions from floodable length considerations (37).

(vi) The number of holds (HOLDSN) is then given by

\[ \text{HOLDSN} = \frac{\text{BAYS}}{\text{NCLPH}} \quad \text{Eq. 5.16} \]
and \( \text{HOLDSN} \) can either be an odd, or even or exact multiple of \( \text{NCLPH} \).

(vii) The total container hold length (\( \text{BLOCKL} \)) is then calculated as, where \( \text{HOLDN} = \text{HOLDSN} \).

<table>
<thead>
<tr>
<th>Bays</th>
<th>No. of bays/hold NCLPH</th>
<th>Total container hold length in m. (( \text{BLOCKL} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Even</td>
<td>2</td>
<td>( \text{HOLDN} \times (2 \times \text{CL} + 2.286) )</td>
</tr>
<tr>
<td>Odd</td>
<td>2</td>
<td>( \text{HOLDN} \times (2 \times \text{CL} + 2.286) + \text{CL} + 1.524 )</td>
</tr>
<tr>
<td>Exact multiple</td>
<td>3</td>
<td>( \text{HOLDN} \times (3 \times \text{CL} + 3.048) )</td>
</tr>
<tr>
<td>&quot; +1</td>
<td>3</td>
<td>( \text{HOLDN} \times (3 \times \text{CL} + 3.048) + \text{CL} + 1.524 )</td>
</tr>
<tr>
<td>&quot; +2</td>
<td>3</td>
<td>( \text{HOLDN} \times (3 \times \text{CL} + 3.048) + 2 \times \text{CL} + 2.286 )</td>
</tr>
<tr>
<td>Exact multiple</td>
<td>4</td>
<td>( \text{HOLDN} \times (4 \times \text{CL} + 3.81) )</td>
</tr>
<tr>
<td>&quot; +1</td>
<td>4</td>
<td>( \text{HOLDN} \times (4 \times \text{CL} + 3.81) + \text{CL} + 1.524 )</td>
</tr>
<tr>
<td>&quot; +2</td>
<td>4</td>
<td>( \text{HOLDN} \times (4 \times \text{CL} + 3.81) + 2 \times \text{CL} + 2.286 )</td>
</tr>
<tr>
<td>&quot; +3</td>
<td>4</td>
<td>( \text{HOLDN} \times (4 \times \text{CL} + 3.81) + 3 \times \text{CL} + 3.048 )</td>
</tr>
</tbody>
</table>

The total clearance/hold was chosen as average of the values indicated in Table 5.6 and given below. These values are for 20' ISO general cargo containers. Clearances for other types of containers can easily be introduced in the program. Table 5.6 gives some indicative values for Reefers and different mixes of containers (e.g. two bays of 20' and one bay of 40' container in a hold).

<table>
<thead>
<tr>
<th>No. of bays/hold</th>
<th>Total clearance/hold in m.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.524</td>
</tr>
</tbody>
</table>

Following are the values of the container hold length calculated by the program and that of some actual ships assuming a 20' container (6058 mm + 35 mm = 6093 mm).
The program results are in most cases lower than the actual ship's data, this being the minimum length possible, and within acceptable limits.

<table>
<thead>
<tr>
<th>Ship Ref. No.</th>
<th>No. of Bays</th>
<th>HOLDSN</th>
<th>No. of bays/hold</th>
<th>Container hold length in m.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NCLPH</td>
<td></td>
<td>Table 5.6</td>
</tr>
<tr>
<td>13</td>
<td>26</td>
<td>Even</td>
<td>2</td>
<td>189.42</td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>odd</td>
<td>2</td>
<td>74.23</td>
</tr>
<tr>
<td>16</td>
<td>18</td>
<td>Exact. Mlt.</td>
<td>3</td>
<td>132.85</td>
</tr>
<tr>
<td>21</td>
<td>16</td>
<td>&quot; +1</td>
<td>3</td>
<td>112.70</td>
</tr>
<tr>
<td>19</td>
<td>23</td>
<td>&quot; +2</td>
<td>3</td>
<td>157.23</td>
</tr>
<tr>
<td>24</td>
<td>24</td>
<td>Exact. Mlt.</td>
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<td>181.45</td>
</tr>
<tr>
<td>22</td>
<td>26</td>
<td>&quot; +3</td>
<td>4</td>
<td>189.59</td>
</tr>
<tr>
<td>25</td>
<td>27</td>
<td>&quot; +3</td>
<td>4</td>
<td>199.48</td>
</tr>
</tbody>
</table>

(b) Machinery space length

There were very few formulae for calculating the length of the engine room. Those that were available were mainly for steam turbine or gas turbine machinery (37,40). Others for diesel machinery (41) were found to be valid for a very small power range or not suitable for parametric studies (42) because it was given as a function of the length of the ship, and as shown in Table 5.7 valid for ships with single screw installation.

To calculate the length of the machinery space, the diesel machinery were subdivided into (a) direct drive diesel (b) geared diesel.

Direct drive diesel:

The ships shown in Table 5.7 were used to develop the engine room length. Different estimating equations were developed for ships with machinery position aft and those with machinery position 3/4 aft. Straight line equations of the form \( y = mx \text{ SHP} + C \) gave good correlation and are indicated.

(a) Single screw ships with machinery aft

The length of the engine room (FLMC) is given by,
<table>
<thead>
<tr>
<th>No.</th>
<th>Ship's Name</th>
<th>Length BP in m.</th>
<th>No. of engines</th>
<th>Position of m/c room</th>
<th>Power in British H.P.</th>
<th>Length of eng. room Actual m.</th>
<th>Program m.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Goldenfels</td>
<td>144.00</td>
<td>S.S. Aft</td>
<td>12250</td>
<td>28.0</td>
<td>26.97</td>
<td>26.77</td>
</tr>
<tr>
<td>2</td>
<td>Table Bay</td>
<td>248.20</td>
<td>S.S. Aft</td>
<td>51360</td>
<td>26.5</td>
<td>27.77</td>
<td>36.73</td>
</tr>
<tr>
<td>3</td>
<td>New Jersey Maru</td>
<td>247.00</td>
<td>T.S. Aft</td>
<td>69600</td>
<td>33.1</td>
<td>32.84</td>
<td>32.84</td>
</tr>
<tr>
<td>4</td>
<td>Oriental Chevalier</td>
<td>192.00</td>
<td>S.S. Aft</td>
<td>29000</td>
<td>37.5</td>
<td>35.14</td>
<td>35.14</td>
</tr>
<tr>
<td>5</td>
<td>Elbe Maru</td>
<td>252.00</td>
<td>Triple Aft</td>
<td>84600</td>
<td>49.97</td>
<td>37.00</td>
<td>37.29</td>
</tr>
<tr>
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<td>Selandia</td>
<td>257.60</td>
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<td>78600</td>
<td>34.14</td>
<td>35.34</td>
<td>38.12</td>
</tr>
<tr>
<td>7</td>
<td>Hakozaki</td>
<td>200.00</td>
<td>S.S. Aft</td>
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<td>30.40</td>
<td>30.17</td>
<td>29.60</td>
</tr>
<tr>
<td>8</td>
<td>Elbe Express</td>
<td>155.00</td>
<td>&quot;</td>
<td>15750</td>
<td>29.05</td>
<td>28.68</td>
<td>28.68</td>
</tr>
<tr>
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<td>C.P. Voyageur</td>
<td>153.00</td>
<td>&quot;</td>
<td>15000</td>
<td>30.40</td>
<td>28.31</td>
<td>28.31</td>
</tr>
<tr>
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<td>Neptune</td>
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<td>25.60</td>
<td>24.76</td>
<td>24.42</td>
</tr>
<tr>
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<td>Kiso Maru</td>
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<td>T.S. Aft</td>
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<td>45.00</td>
<td>35.73</td>
<td>35.73</td>
</tr>
<tr>
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<td>Verranzano</td>
<td>248.00</td>
<td>&quot;</td>
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<td>35.64</td>
<td>35.73</td>
<td>35.73</td>
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<td>23.17</td>
<td>23.17</td>
</tr>
<tr>
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<td>Svendborg</td>
<td>178.00</td>
<td>S.S. Aft</td>
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<td>25.83</td>
<td>25.83</td>
</tr>
<tr>
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<td>California</td>
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<td>24.75</td>
<td>33.72</td>
<td>33.72</td>
</tr>
<tr>
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<td>Act I</td>
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<td>&quot;</td>
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<td>30.48</td>
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<td>35.63</td>
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<td>29.80</td>
<td>30.17</td>
<td>29.60</td>
</tr>
<tr>
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<td>Dart America</td>
<td>218.01</td>
<td>&quot;</td>
<td>29000</td>
<td>34.40</td>
<td>35.14</td>
<td>35.14</td>
</tr>
<tr>
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<td>Hawaiiin</td>
<td>206.35</td>
<td>&quot;</td>
<td>32000</td>
<td>33.53</td>
<td>36.60</td>
<td>36.60</td>
</tr>
<tr>
<td>20</td>
<td>Enterprise</td>
<td>147.00</td>
<td>&quot;</td>
<td>12000</td>
<td>19.40</td>
<td>19.35</td>
<td>21.75</td>
</tr>
<tr>
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<td>City of Plymouth</td>
<td>96.31</td>
<td>&quot;</td>
<td>5500</td>
<td>14.5</td>
<td>23.68</td>
<td>23.68</td>
</tr>
<tr>
<td>22</td>
<td>Keshu Maru</td>
<td>175.00</td>
<td>&quot;</td>
<td>27600</td>
<td>25.70</td>
<td>26.96</td>
<td>25.90</td>
</tr>
<tr>
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<td>Golden Gate Bridge</td>
<td>175.00</td>
<td>&quot;</td>
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<td>25.00</td>
<td>26.91</td>
<td>26.91</td>
</tr>
<tr>
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<td>America Maru</td>
<td>175.00</td>
<td>&quot;</td>
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<td>25.00</td>
<td>27.15</td>
<td>27.15</td>
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<td>27.05</td>
<td>27.05</td>
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<td>29000</td>
<td>37.95</td>
<td>35.14</td>
<td>35.14</td>
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</table>

Note 1.* Pawlowski (42) gives the following expression for calculating the length of engine room (FLMC) for ships with direct drive diesel.

\[
FLMC_{(\frac{3}{4} Aft)} = 0.148 \times L \quad \text{m.}
\]

2.† Assumed twin screw.

3.‡ British horsepower=746 watts and PS(Metric horsepower)=736 watts.
(correlation 0.82, 9 data points)

$$FLMC = 4.665 \times 10^{-4} \times SHP + 20.958 \text{ m}$$  \hspace{1cm} \text{Eq. 5.17}

(b) Single screw ships with machinery 3/4 aft

$$FLMC = 4.583 \times 10^{-4} \times SHP + 13.704 \text{ m}$$  \hspace{1cm} \text{Eq. 5.18}

(correlation 0.933, 10 data points)

The engine room length is equal to the length of the engine plus some space for, and aft of the engine. The length of direct drive diesel engines was plotted for various makes of engines, which gives an equation of the form (mean line)

$$\text{length of direct drive engine} = 4.875 \times 10^{-4} \times SHP + 5.82 \text{ m}$$  \hspace{1cm} \text{Eq. 5.19}

The Equations 5.17 and 5.18 were therefore modified to give the slope given by Eq. 5.19; and are given by

$$FLMC_{SS}(\text{aft}) = 4.875 \times 10^{-4} \times SHP + 21 \text{ m}$$  \hspace{1cm} \text{Eq. 5.20}

$$FLMC_{SS}(3/4 \text{ aft}) = 4.875 \times 10^{-4} \times SHP + 13.50 \text{ m.}$$  \hspace{1cm} \text{Eq. 5.21}

Eq. 5.19, 5.20, 5.21 are shown in Fig. 5.10. The choice of machinery position is input by the user through the control parameter IPMC.

(c) Twin screw installation.

The maximum power that can be delivered through a single shaft is assumed to be 50,000 h.p.. Therefore the program automatically assumes that above this power the ship is a twin engine, twin screw installation and the machinery position is 3/4 aft.

The shaft horse power of the ship is scaled as follows:

$$\text{SHP} = \frac{\text{SHP}}{2} \times 1.14$$ and the Eq. 5.21 used to calculate the engine room length. e.g. for Ship No.12 \(\text{SHP} = \frac{80000}{2} \times 1.14 = 45600 \text{ h.p.} \) and Eq. 5.21 gives \(\text{FLMC} = 35.73\), actual value is 35.64. As Table 5.7 indicates these equations give a fairly good approximation to machinery space length.

**Geared Diesel:**

Container ships of smaller size usually have geared diesel installation. Table 5.8 indicates some container ships.
Fig. 5.10. Engine Room Length versus installed power
(Direct Drive Diesel plant)

Length of Engine Room, metres

4.875 x 10^-4 x SHP + 21.0 (PROGRAM)

4.875 x 10^-4 x SHP + 13.5 (PROGRAM)

Eq. 5.17

Eq. 5.18

Length of Engine = 4.875 x 10^-4 x SHP + 5.82

TABLE 5.8. Length of engine room for ships with geared diesel installation.

<table>
<thead>
<tr>
<th>No.</th>
<th>Ship's Name</th>
<th>Length BP in m.</th>
<th>No. of engines/propeller</th>
<th>Position of m/y room</th>
<th>Power in British H.P.</th>
<th>Length of Eng. Room</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fiery Cross Isle</td>
<td>133.60</td>
<td>1 1</td>
<td>Aft</td>
<td>17500</td>
<td>21.9 24.36 -</td>
</tr>
<tr>
<td>2</td>
<td>Manchester Vigour</td>
<td>103.10</td>
<td>&quot;</td>
<td>&quot;</td>
<td>6000</td>
<td>13.4 15.567 -</td>
</tr>
<tr>
<td>3</td>
<td>Atlantic Jamaican</td>
<td>79.15</td>
<td>&quot;</td>
<td>&quot;</td>
<td>3200</td>
<td>12.81 13.43 12.26</td>
</tr>
<tr>
<td>4</td>
<td>Brian Boromime</td>
<td>99.97</td>
<td>2 2</td>
<td>&quot;</td>
<td>4200</td>
<td>14.70 14.19 15.49</td>
</tr>
<tr>
<td>5</td>
<td>Atlantic Marseille</td>
<td>154.70</td>
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<td>&quot;</td>
<td>18000</td>
<td>26.00 24.74 -</td>
</tr>
<tr>
<td>6</td>
<td>Fort Royal</td>
<td>198.00</td>
<td>2 2</td>
<td>Aft</td>
<td>36000</td>
<td>28.09 - -</td>
</tr>
<tr>
<td>7</td>
<td>Axel Johnson</td>
<td>157.20</td>
<td>4 2</td>
<td>&quot;</td>
<td>26000</td>
<td>17.68 - -</td>
</tr>
<tr>
<td>8</td>
<td>Sea Freight liner</td>
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<td>Aft</td>
<td>3780</td>
<td>17.70 13.87 -</td>
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<tr>
<td>9</td>
<td>Manchester Challenge</td>
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<td>2 1</td>
<td>&quot;</td>
<td>16380</td>
<td>24.38 23.50 -</td>
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<tr>
<td>10</td>
<td>Hustler Class</td>
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<td>&quot;</td>
<td>3200</td>
<td>12.81 13.43 12.22</td>
</tr>
<tr>
<td>11</td>
<td>Tarross</td>
<td>78.84</td>
<td>1 1</td>
<td>&quot;</td>
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<td>12.81 13.43 12.22</td>
</tr>
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<td>Strider</td>
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<td>7000</td>
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<td>13</td>
<td>Wicklow</td>
<td>92.00</td>
<td>1 1</td>
<td>&quot;</td>
<td>3900</td>
<td>15.24 13.96 14.26</td>
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<td>14</td>
<td>Rohdri Mawr</td>
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<td>15</td>
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<td>Jeddah Crown</td>
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<td>8900</td>
<td>17.60 17.78 -</td>
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<td>17</td>
<td>Bell 'R' Class</td>
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<td>1 1</td>
<td>&quot;</td>
<td>2100</td>
<td>21.26 12.58 11.16</td>
</tr>
</tbody>
</table>

Note 1. * Pawlowski (42) gives the following equation for ships less than 100 m. and machinery position aft. Length of machinery space FLMC is given by,

$$FLMC_{(aft)} = 0.155 \times LB P \ m.$$
ships with geared diesel installation and the length of the engine room. Fig. 5.11 shows the plot of the length of the medium speed diesel engine, valid for 2600-30600 hp range. Because of the gearbox and other ancillaries it was found that the length of the engine room could not be derived directly from the length of the engine.

Instead the ships shown in Table 5.8 were used to estimate the length of the engine room and is given by:

For single screw installations with machinery room aft,

\[ FLMC_{SS} = 6.887 \times 10^{-4} \times SHP + 10.75 \text{ m} \quad \text{Eq. 5.22} \]

(8 data points, correlation 0.897)

As shown in Table 5.8 most ships with geared diesel installation are of low power and the machinery position is usually aft. So a single equation was fitted for both twin screw and single screw installation which gave better correlation (13 points, correlation 0.92). In the program therefore ships with less than 10000 h.p. are assumed to have geared diesel installation with machinery room aft, and engine room length is given by

\[ FLMC(S.\ S. \ & \ T.\ S.) = 7.645 \times 10^{-4} \times SHP + 10.98 \text{ Eq. 5.23} \]

A comparative evaluation (Table 5.8) shows that the equation gives a good approximation to machinery room length, with the method given by Pawlowski (42).

(c) Length of peaks

Table 5.9 shows the length of the aft peak and fore peak of containerships as a percentage of LBP. Whereas aft peak length compared to the fore peak length as a percentage of LBP shows a larger variation, the overall length of the peaks as a percentage of LBP shows lesser variation. The value of \( LFP + LAP \) varies from 6% to 15%. In the program the combined length of peaks is assumed to be 10% of LBP. The minimum length between perpendiculars is then given by

\[ FLMIN = \text{length of the container holds (BLOCKL)} + \text{length of the machinery spaces (FLMC)} + \text{length of peaks} \text{ m} \quad \text{Eq. 5.24} \]

The program ensures that the designs generated have LBP
Fig. 5.11. Length of Engine Room versus installed power (Geared Drive Diesel plant)

- Length of engine room, metres
- Installed power, horse power (British)
- Length of medium speed diesel engine
- Length of S.S. & I.S. M/yr aft

Equation 1: $7.645 \times 10^{-4} \times \text{SHP} + 10.98$
Equation 2: $6.887 \times 10^{-4} \times \text{SHP} + 10.75$ m/yr aft
Table 5.9. Length of peaks.

<table>
<thead>
<tr>
<th></th>
<th>LFP length of fore-peak m.</th>
<th>Length of cargo spaces m.</th>
<th>Length of deep tk. m.</th>
<th>LFP length of aft peak m</th>
<th>LFP LBP %</th>
<th>LAP LBP %</th>
<th>LFP + LAP LBP %</th>
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<tr>
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<td>LFP length of fore-peak m.</td>
<td>Length of cargo spaces m.</td>
<td>Length of deep tk. m.</td>
<td>LAP length of aft peak m.</td>
<td>LFP LBP % age</td>
<td>LAP LBP % age</td>
<td>LFP + LAP LBP % age</td>
</tr>
<tr>
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<td>7.32</td>
<td>8.46</td>
<td>4.78</td>
<td>13.24</td>
</tr>
</tbody>
</table>
greater than this (FLMIN) value. The subroutine subprogram DESIGN calculates the minimum length between perpendiculars.

5.5 Draft

Container ships are never very deep draught ships. The reasons are (a) the design deadweight of most container ships can be obtained at a draft less than that obtainable with a Type B-freeboard.

(b) Containerships are essentially stability limited ships and therefore the total containers that can be carried are governed by the stability constraints.

(c) Though a 20' container can carry 18.29 tonnes (18 tons) of cargo the average cargo weight carried is about 12-15 tonnes (15) and on the North Atlantic route on nearly 60% of the time the average weight per container is 14.8 tonnes (203).

Other factors which determine draft are depth at the harbour approach and channel restrictions if any. The largest containerships have drafts of about 13 m (see Fig. 5.5), and the design draft of a containership is usually about 1 to 2 m below that allowable by the minimum freeboard.

Since the average container weight is dependent on the route characteristics, the user can input a constraint on the maximum allowable average weight of each container.

In Chapter 13, it is shown how a reasonable design draft can be selected. In the program the draft is constrained by the B/T ratio and the minimum freeboard requirements.

The minimum draft (TMIN) allowable by B/T constraint is

\[ TMIN = \frac{B}{3.75} \text{ m} \quad \text{Eq. 5.25} \]

and the maximum draft (TMAX) allowable by B/T constraint is

\[ TMAX = \frac{B}{2.25} \text{ m or } TMAX = D - \text{minimum freeboard} \text{ m} \quad \text{Eq. 5.26} \]

 whichever is less.
5.6. Block Coefficient

In order to maximise the number of containers it would be desirable to have a high block coefficient. Thus the optimum containership from a stowage point of view would be a rectangular barge.

There are various formulae being used for preliminary design studies, of which the more common are given below.

\[ C_b = 1.137 - 0.6 \frac{V}{\sqrt{L}} \] (Van Lammeren) \hspace{1cm} (43) Eq. 5.27

\[ C_b = 1.06 - 0.5 \frac{V}{\sqrt{L}} \] (Ayre) \hspace{1cm} (43) Eq. 5.28

\[ C_b = 1.22 - 0.709 \frac{V}{\sqrt{L}} \] (Minorsky) \hspace{1cm} (43) Eq. 5.29

\[ C_b = 1 - \frac{3}{8} x (B/L + 1) \frac{V_T}{\sqrt{L}} \] (Telfer) \hspace{1cm} (43) Eq. 5.30

\[ C_b = 0.65 + 0.95 \frac{V}{\sqrt{L}} - 1.2 \left( \frac{V}{\sqrt{L}} \right)^2 \] (Sabit) \hspace{1cm} (43) Eq. 5.31

\[ C_b = K - \frac{V}{3.62 x \sqrt{L}} \] (Alexander),
\[ K = 1.12 \text{ to } 1.03 \] \hspace{1cm} (35) Eq. 5.32

\[ C_b = 1.216 - 0.392 \frac{V}{\sqrt{L}} \] (Silverleaf) \hspace{1cm} (43) Eq. 5.33

\[ C_b = 0.8217 x L^{0.42} B^{-0.3072} T^{0.1721} V^{-0.6135} \] (Katsoulis) \hspace{1cm} (44) Eq. 5.34

\[ C_b = 0.7 + 1/8 \tan^{-1} 25(0.23 - F_n) \] (Townsin) \hspace{1cm} (45) Eq. 5.35

Eq. 5.27 to Eq. 5.31 the dimensions are in feet, for Eq. 5.32 to Eq. 5.35 the dimensions are in metres; and the speed is in knots in all equations. These empirical formulae are either the result of regression analysis of existing ships or models, and do not take into account, when choosing the block coefficient the economic factors such as fuel price, shipbuilding costs and other operating conditions.

Therefore in the program block coefficient is made an independent variable and the optimum is determined taking into account the various operating conditions and economic factors. Figure 5.12 shows the optimum block coefficient determined by the program together with the above equations.
Fig. 5.12. Block coefficient versus speed length ratio.
The block coefficient was varied from 0.50 to 0.70 which covers most of the containerships for speeds length ratio of 0.40 to 1.5.

5.7. Structural design considerations

Containerships are 'open' ships because they have total hatch width of nearly 80% of the ship's breadth and extending nearly 60-77% of the ship's length. This has given rise to two basic problems as far as structural strength is concerned. Firstly difficulty in providing sufficient section material to satisfy requirements of longitudinal strength and, secondly that an 'open' section lacks torsional rigidity and is prone to warp, causing additional longitudinal stresses which augment those due to longitudinal bending (22). Meek (21) and Clemmetsen (23) discuss these problems in detail, and Rapo (20) gives a simple approach which can be incorporated in the preliminary design stage to ensure adequate structural strength.

To ensure adequacy of hull girder stiffness requirements as given by Classification Society Rules (38) an upper limit on the value of $L/D = 15$ is given (27).

Nakamura (24) arrives at the following limiting values of $L/D$ ratios for ships designed with adequate longitudinal strength.

<table>
<thead>
<tr>
<th>$L_{BP}$ in m.</th>
<th>150</th>
<th>175</th>
<th>200</th>
<th>214.67</th>
<th>250</th>
<th>275</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rows of containers</td>
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<td>9</td>
<td>9</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Tiers of containers</td>
<td>-</td>
<td>-</td>
<td>&gt;6</td>
<td>&gt;7</td>
<td>&gt;8</td>
<td>9</td>
</tr>
<tr>
<td>Rows of hatchways</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Breadth in m.</td>
<td>22.5</td>
<td>26.25</td>
<td>30</td>
<td>32.20</td>
<td>32.20</td>
<td>32.20</td>
</tr>
</tbody>
</table>

Though Rapo (20) and Nakamura (24) give some simplistic approach to structural design of containerships, this was not
incorporated, since it was found that the preliminary design program will require input data which are not readily available, and therefore left for future development.

Therefore the only structural consideration that the program incorporates is to ensure adequate hull girder stiffness by limiting the value of L/D between 10 and 14.5.

5.8. Gross and net tonnage

Gross registered tonnage was made a function of L, B and D and the net register tonnage was made a function of GRT. Straight line equations fitted to existing containerships gave good correlation.

Gross Register tonnage (GRT) = 0.237 x L x B x D + 995 tons
Eq. 5.36

Net Register tonnage (NRT) = 0.585 x GRT + 110 tons
Eq. 5.37

A check with another estimating equation developed by Chapman (46) showed them to lie in good agreement. The relationship between GRT and LBD is shown in Fig. 5.13 and Fig. 5.14 shows the relationship between GRT and NRT.

5.9. Freeboard Type-B

Cameron and Martin (47) gives a computer algorithm for the calculation of freeboard for Type-A and Type-B ships. In this thesis a simpler approach was adopted. The subroutine subprogram FREBRD calculates the tabular freeboard as well as the minimum freeboard by taking into account the correction for block coefficient, depth and sheer. The procedure is similar to one given by Kupras (48). The tabular freeboard given by the Load Line Regulations (49) was approximated by two polynomials. Tabular freeboards from length BP 100 m to 250 m and length BP 251 m to 365 m was fitted by two sixth order polynomials by the method of Least Squares (50). The method is valid for Type-B ships of length greater than 100 m.

(a) Tabular freeboard (TABFBD) is given by

\[ \text{TABFBD} = A_0 + A_1 x + A_2 x^2 + A_3 x^3 + A_4 x^4 + A_5 x^5 + A_6 x^6 \text{ in mm.} \]
Eq. 5.38

where the values of coefficients are as given overleaf.
Fig. 5.13. L x B x D versus Gross Registered Tonnage.

No. of Data points 52
Correlation 0.983
Fig. 5.14. Gross Register Tonnage versus Net Register Tonnage.

Number of data points = 34
Correlation = 0.99

Gross Register Tonnage, Tons

Net Register Tonnage, Tons

103
<table>
<thead>
<tr>
<th>No. of data</th>
<th>Length BP metres</th>
<th>$A_0$</th>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_3$</th>
<th>$A_4$</th>
<th>$A_5$</th>
<th>$A_6$</th>
<th>Sum of Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>151</td>
<td>100 - 250</td>
<td>230.09</td>
<td>-5.925</td>
<td>0.2451</td>
<td>-0.913</td>
<td>0.796</td>
<td>0.239</td>
<td>-0.508</td>
<td>$0.989 \times 10^6$</td>
</tr>
<tr>
<td>115</td>
<td>251 - 365</td>
<td>-15996.63</td>
<td>373.45</td>
<td>-3.367</td>
<td>0.171</td>
<td>-0.491</td>
<td>0.744</td>
<td>0.464</td>
<td>$0.109 \times 10^4$</td>
</tr>
</tbody>
</table>
(b) Correction for block coefficient

Block coefficient at 0.85 depth = \( C_b + (1.0 - C_b) \times \frac{(0.85 \times D - T)/(3.0 \times T)}{1.36} \)  
Eq. 5.39

for \( C_b \) at \( 0.85D > 0.68 \)

Corrected tabular freeboard \( TABFBD = TABFBD \) (Eq. 5.38)

\[ x \frac{(C_{b0.85D} + 0.68)}{1.36} \] mm  
Eq. 5.40

(c) Correction for depth (CORRDE)

for \( D \leq \frac{LBP}{15} \) correction for depth (CORRDE) = 0 mm

for \( D > \frac{LBP}{15} \) correction for depth (CORRDE) = \((D - \frac{LBP}{15}) \times R\) mm  
Eq. 5.41

where for \( LBP < 120.0 \) m, \( R = LBP/0.48 \) mm

\( LBP \geq 120.0 \) m, \( R = 250 \) mm

(d) sheer correction; assuming actual sheer is zero and the effective length of superstructure is 0.3xLBP (48). Standard sheer (SHEERS) is given by,

\[ \text{SHEERS} = \frac{(200.0 \times LBP + 6000)/48.0}{\text{mm}} \]

Then sheer correction (CORSHR) = \((0.75 - \frac{S}{2.0}) \times \text{SHEERS}\) mm  
Eq. 5.42

where \( S = 0.3 \times \text{LBP} \)

(e) Therefore minimum freeboard (FBCAL) is

\[
\text{FBCAL} = \text{TABFBD} + \text{depth correction (CORRDE)} + \text{sheer correction (CORSHR)} \text{ mm.} \]

\[ \text{FBCAL} = \text{FBCAL} \times 0.001 \text{ in m.} \]

Containerships attain their dead weight requirements at drafts which are less than those allowed by minimum freeboard rules. A check of actual freeboards with those calculated by the program shows that the available freeboard is more than the minimum freeboard in all cases.
<table>
<thead>
<tr>
<th>Ship's Name</th>
<th>L (m)</th>
<th>D (m)</th>
<th>T (m)</th>
<th>CB</th>
<th>D-T Actual (m)</th>
<th>Minimum* (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tokyo Bay</td>
<td>274.32</td>
<td>24.60</td>
<td>13.03</td>
<td>0.595</td>
<td>11.57</td>
<td>5.14</td>
</tr>
<tr>
<td>Nihon</td>
<td>257.60</td>
<td>23.91</td>
<td>11.58</td>
<td>0.576</td>
<td>12.33</td>
<td>7.418</td>
</tr>
<tr>
<td>Euroliner</td>
<td>224.96</td>
<td>19.18</td>
<td>10.702</td>
<td>0.550</td>
<td>8.478</td>
<td>6.860</td>
</tr>
<tr>
<td>Verranzano</td>
<td>248.04</td>
<td>19.89</td>
<td>11.989</td>
<td>0.594</td>
<td>7.901</td>
<td>4.183</td>
</tr>
<tr>
<td>Maersk Ship</td>
<td>194.50</td>
<td>18.70</td>
<td>11.190</td>
<td>0.530</td>
<td>7.510</td>
<td>4.180</td>
</tr>
</tbody>
</table>

* By Program
CHAPTER 6
LIGHTSHIP WEIGHT AND CENTRE OF GRAVITY ESTIMATES

6.0 INTRODUCTION
6.1 STEEL WEIGHT
6.2 OUTFIT AND HULL ENGINEERING WEIGHT
6.3 MACHINERY WEIGHT
6.4 GUIDE WEIGHT
6.5 CENTRE OF GRAVITY OF STEEL, OUTFIT, MACHINERY AND GUIDE WEIGHT
6.6 LIGHTSHIP WEIGHT AND CENTRE OF GRAVITY
6.0 INTRODUCTION

The light ship weight is composed of
(a) steel weight
(b) outfit weight
(c) machinery weight
(d) guide weight
(e) margin on light ship weight.

The following subsections deal with methods of estimating each of these weights. Though many estimating equations have been suggested in the past for estimating each of the above weight groups, they are not consistent with actual data and with each other.

This is mainly due to the fact that many of these empirical relationships were established when there were very few purpose built or newly built container ships. The empirical relationships were verified with general cargo ships which were converted into container ships, resulting in higher lightship weight.

Also because of technological advance the weight of containerships today are much lighter and structurally stronger than their predecessors.

The second reason for the formulae not being consistent with each other is due to the grouping of items in each of the major categories of steel, outfit and machinery. Often the range of ship size over which the estimating equations are valid differ and therefore are not comparable with each other. In the following subsections the weights estimated by different formulae suggested in past studies are compared with the one adopted in the algorithm.

A family of ships of size 600 TEU to 3000 TEU and speed 18 knots to 27 knots and some other containerships for which weight data were available are compared with the one adopted in the program and the error indicated.

The literature search for estimating the centre of gravity of steel, outfit, machinery and guide weight was less satisfactory. So the latest available formulation is adopted, validated with some ships data.
6.1. STEEL WEIGHT (WS)

The steel weight is obviously the most significant percentage of the total light ship weight, and as such, it is essential that a good and reliable weight be estimated. Additionally, the construction cost of the ship is also related to the steel weight.

There were many methods available for calculating the net steel weight. Most of the methods or formulae are derived by application of regression analysis on existing ship data and indices allotted to the various dimensions i.e. Length (L), Breadth (B), Depth (D), draft (T) and block coefficient (Cb). These indices vary widely depending on the influence of each of the dimensions. Moreover in many cases the influencing parameters appear to have little physical significance.

The various methods suggested in the literature specifically for calculating steel weights of containerships are mentioned below, together with their comparative evaluation with some actual ship data. A summary of the various equations are shown in Table 6.1.

**METHOD 1:** The first method was suggested by Benford (51) in 1965 and was modified and adopted by Miller (52) in 1970 as a part of containership design model. Miller verified that the steel weight of a containership is very close to the equivalent steel weight of a conventional cargo ship.

**METHOD 2:** The first method used by Miller was subsequently modified in another study by Marad (53) 1973 and also used by Hancock (54) 1972 in his containership study. The first term 340 in the equation (see Table 6.1) was updated to 380 in both the studies, reflecting a higher steel weight for a containership compared to general cargo ships for which it was originally developed.

**METHOD 3:** The third formulation was used in a containership study by Chryssostomidis (37) 1968, and was developed at a time when the first generation of containerships were just being built. It was subsequently used in another container ship
### TABLE 6.1. Summary of steel weight equations.

<table>
<thead>
<tr>
<th>Method/Ship Type</th>
<th>Equation</th>
<th>Equation</th>
<th>Ref.</th>
<th>Yr.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dimensions in feet</td>
<td>Dimensions in metres</td>
<td>Weight in long tons</td>
<td>Weight in tonnes</td>
</tr>
<tr>
<td>1</td>
<td>$WS_1 = 340 \times \left( \frac{CN}{1000} \right)^{0.9} \times \left( 0.675 + \frac{CB}{2} \right) \times \left( 0.00585 \times \left( \frac{L}{D} - 8.3 \right)^{1.8} + 0.939 \right)$</td>
<td>$WS_1 = 8407 \left( \frac{CN}{1000} \right)^{0.9} \times \left( 0.675 + \frac{CB}{2} \right) \times \left( 0.00585 \times \left( \frac{L}{D} - 8.3 \right)^{1.8} + 0.939 \right)$</td>
<td>51* (1)</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>$WS_2 = WS_1 \times \frac{380}{340}$</td>
<td>$WS_2 = WS_1 \times 9396/8407$</td>
<td>53</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>$WS_3 = 2.107 \times \left( \frac{L \times (B+D) \times K_9}{100} \right)^{1.19}$</td>
<td>$WS_3 = 35.558 \left( \frac{L \times (B+D)}{100} \right)^{1.19}$</td>
<td>37</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>$FSTWT_1 = 7 \times 10^{-4} L^{1.76} B^{0.712} D^{0.374}$</td>
<td>$FSTWT_1 = 205.86 \times 10^{-4} L^{1.76} B^{0.712} D^{0.374}$</td>
<td>46</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>$DHWT_1 = 129.63 \times 10^{-4} \times CN$</td>
<td>$DHWT_1 = 4555 \times 10^{-4} \times CN$</td>
<td>39</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>$CN = L \times B \times D/100.$</td>
<td>$WS_4 = FSTWT_1 + DHWT_1$</td>
<td>55</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>$FSTWT_2 = VU \times C_1 \times C_2 \times C_3 \times C_4 \times C_5 \times C_6 \times C_7$</td>
<td>$CN = L \times B \times D/100.$</td>
<td>56</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>$DHWT_2 = DHWT_1$</td>
<td>$WS_5 = FSTWT_2 + DHWT_1$</td>
<td>46</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>$WS_6 = FSTWT_2 + DHWT_3$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$WTFCLS = 0.014 \times L \times B$</td>
<td>$DHWT_3 = 160 + 0.00874 \times L \times B$</td>
<td>48</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>$DKHWT = 160 + 0.00874 \times L \times B$</td>
<td>$DHWT_3 = WTFCLS + DKHWT$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>$WS_7 = FSTWT_1 + DHWT_3$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>$WS_8 = WS'_1 (1 + 0.5(CBD-0.70))$</td>
<td>$WS'<em>1 = K \times E</em>{1.36}$</td>
<td>35</td>
<td>77</td>
</tr>
<tr>
<td>9</td>
<td>$WS_9 = 681.82 + 227.27 \times \left( \frac{LBD}{100} \right) \times 10^{-3}$ (based on standard freighters) equation estimated from graph</td>
<td>$WS_9 = 6.93 + 0.08154 \times L \times B \times D$</td>
<td>58</td>
<td>62</td>
</tr>
<tr>
<td>10</td>
<td>$WS_{10} =$ (See main text)</td>
<td></td>
<td>59</td>
<td>70</td>
</tr>
</tbody>
</table>

**NOTE**

(1) Benford had another term in the equation \((1 + 0.36 \times \frac{L_8}{L_{BP}})\) where \(L_8 = \text{length of the superstructure.}\)

(2) \(CN = L \times B \times D/100.\)
study by Fortson (40) in 1974.

**METHOD 4:** The fourth formulation was the first steel weight estimating equation to be proposed, specifically for containerships. It was developed by Chapman (46) in 1969 and has been used subsequently in other containership studies, e.g. Erichsen (39) 1971 who validated it with eleven ships with known steel weight and later on by Swift (55) in 1974 who further validated it with 7 ships with known steel weight. The formula is applicable for ships of size from 800 Teu to 3500 Teu and speeds between 20 to 35 knots. The net steel weight is subdivided into hull steel weight or flush steel weight (FSTWT1) and deck house weight (DHWT1). Later in the section it is shown that this formula may be used for currently built ships too, and is adopted in the parametric study.

**METHOD 5:** This method was proposed by Schneekluth (56) 1972 for calculating the hull steel weight (FSTWT2). The method developed was verified with actual steel weight of ships built during 1967-1971. It was found for containerships that the steel weight is 2-10% higher than the corresponding general cargo ships.

The hull steel weight is given by

\[
FSTWT2 = VU x C_1 x C_2 x C_3 x C_4 x C_5 x C_6 x C_7
\]

where \( C_1 \) = 0.103 \((1 + 17(L-110)^2/10^6) \) (t/m³)

where \( C_1 \) varies from 0.103 t/m³ for LBP = 110 m to 0.16 t/m³ for LBP = 290 m.

\[
C_2 = (1.0 + 0.033 (L/D - 12))
\]

\[
C_3 = (1.0 + 0.06(n - \frac{D}{4(m)})}, \text{ where } n = \text{number of decks}
\]

\[
C_4 = (1.0 + 0.04(L/B - 6.5))
\]

\[
C_5 = (1.0 + 0.2(T/D - 0.85))
\]

\[
C_6 = (0.96 + 1.2(0.85 - CBD)^2)
\]

\[
C_7 = (1.0 + 0.75 \times \text{CBD} \times (C_6 - 0.98))
\]

where CBD = block coefficient of \( T = D \) and estimated as

\[
\text{CBD} = C^b + (1 - C^b)(D-T)/3T
\]
\[ VU = L \times B \times D \times \text{CBD} \times 1.02 \quad (m^3) \]

Other corrections for differences in mode of construction, material or ship type are given in (56). This equation was used to verify the flush steel weight calculated by Method 4. To calculate the steelweight it was assumed deckhouse weight is equal to deckhouse weight given by Method 4.

**METHOD 6:**

Nowacki (48) 1975 proposed an equation to determine the deckhouse weight (DHWT3), this was added to the flush steel weight (FSTWT2) of Method 5 to see if the accuracy of Method 5 was improved or not.

**METHOD 7:**

In this method the flush steel weight (FSWT1) was added to the deckhouse weight (DHWT3) estimated by Nowacki to see if the accuracy of Method 4 was improved or not.

**METHOD 8:**

This method was also used in the computer algorithm as an alternative to Chapman's, Method 4. It is based on a method developed by Watson & Gilfillan (35) 1977. The steel weight is estimated as follows:

The net steel weight (WS8) is assumed to be directly related to the hull numeral \( E \). This numeral was chosen because it was applicable to a wide range of ship types. The value of \( E \) is given by

\[
E = L \times (B + T) + 0.85 \times L \times (D - T) + 0.85 \sum 1_1 h_1 + 0.75 \sum 1_2 h_2 \quad (m^2)
\]

where \( 1_1, h_1 \) are length and height of full width erections and \( 1_2, h_2 \) are the length and height of houses.

The value of the third term and the fourth term in the equation was assumed to vary between 200-300 m\(^2\) in the algorithm. Since \( E \) attaches no importance to fullness, the steel weight (WS) was related to a standard block coefficient of 0.70 at 0.8 of the depth. Where

\[
WS' = K \times E^{1.36} \quad \text{(tonnes)}
\]

where \( K \) is the steel weight factor (STEELF) input by the user. The value of \( K \) given in (35) was assumed to vary from 0.033
to 0.040 for 6000 < E < 13000 and validated for 3 container
ships. In the present thesis the steel weight of 45 contain-
erships (Nos.1 to 32 (1968)(57)) and 32 to 45 collected for
this study, (Table 6.2) was used to establish an estimating
equation for the value of K.

Four values of K were determined $K_{\text{min}i}$ and $K_{\text{max}i}$, corresponding to the two values of $E_{\text{min}}$ and $E_{\text{max}}$.

$$E_{\text{min}} = L \times (B + T) + 0.85 \times L \times (D - T) + 200 \text{ m}^2$$

$$E_{\text{max}} = L \times (B + T) + 0.85 \times L \times (D - T) + 300 \text{ m}^2$$

The values of $K_{\text{min}i}$ and $K_{\text{max}i}$ are given in Table 6.3 corresponding to $E_{\text{max}}$ and $E_{\text{min}}$ respectively. The minimum $E$ value was 5000 and maximum 16800. $K_{\text{MIN1}}$ and $K_{\text{MAX1}}$ are steel factors w.r.t. actual steel weight and $K_{\text{MIN2}}$ and $K_{\text{MAX2}}$ are the steelweight factors w.r.t. weight determined by Method 4 and also used in the algorithm. The values of $K_{\text{MAX2}}$ and $K_{\text{MAX1}}$ are plotted against $E$ in Fig. 6.1. With increase in speed for a particular $T_{\text{Teu}}$, $K_{\text{MAX1}}$ tends to decrease from a maximum value to a minimum value whereas opposite seems to be the case for $K_{\text{MAX2}}$, with increase in speed for a particular $T_{\text{Teu}}$, the value increases from a low value to a higher value. This is only for data points 1-32 which are a bit dated. And it is apparent from Fig. 6.2, which shows the $L \times (B + D)/100$ plotted against actual ship data (1-45) and the line of representative containership data from (27) 1980 that the actual steel weight at lower speeds for a particular $T_{\text{Teu}}$ are overestimated for data points (1-32). The trend is obviously increasing value of $K$ with increase in $E$ and speeds. An analysis of weights for (1-45) by Method 4 gave the following approximate equations of $K$

$$K = mE' - C$$

$$= (n \times T_{\text{Teu}} + b) \times E' - C'$$

$$= (1267 \times 10^{-10} \times T_{\text{Teu}} + 6067 \times 10^{-7})E' - 0.00842$$

where $E' = L \times (B + D)/100 \text{ m}^2$

There was lack of data to establish a better equation. $E$ versus $K$ gave a poorer fit to the data available. $K$ is thus left as an input data by the user. For parametric study Method 4 was used as indicated earlier.
6.2

Table

Lbp

Principal

BD

Particulars

and weights

T

Cb

v

of

containershipe

RR1.

SHP

NO.
ProP.

WWWW
Bomg

115

15100

I

4355

2287

980

549

115

18000

I

4406

2296

1178

544

2.150.57

23.77 13.41

9.14 o. 631 18.0
9. I4 0.609 19.0

3.156.06

23.77 13.41

9.14

0.562

21.0

115

22400

I

4460

2312

1483

530

4.160.93

23.77 13.41

9.14

0.516

23.0

115

28200

1

4490

2327

1889

520

5.159.41

27.43 15.85

9.14

0.652

J8.0

no

18000

I

5970

2435

1178

679

6.162.15

27.43 15.85

9.14

0.628

i9.0

IIO

20600

I

6001

2445

1356

675

7.166.72

27.43 15.85

9.14

0.58I

21.0

IN

26100

I

6021

2461

1747

668

8.171.60

27.43 15.85

9.14

0.536

23.0

110

31600

I

6061

2477

2113

650

9.179.20

27.43 15.85

9.14

0.683

18.0

110

18300

I

68i4

2513

1194

959

27.43 15.85

9.14

0.657

19.0

110

21100 .1

6775

2517

1392

955

184.41 27.43 15.85

9.14

0.610

21.0

iio

27000

1

6764

2530

1803

945

12.188.98

27.43 15.85

9.14

0.564

23.0

110

33500

I

6773

2546

2260

927

13.193.55

27.43 15.85

9.14

0.521

25.0

IN

41000

1

6783

2561

1600

924

14.196.90

30.48 15.85

9.14

0.703

18.0

110

21161

I

8239

2668

1392

1198

15.198.12

30.48 15.85

9.14

0.679

19.0

110

1600

1194

9.14

0.632

21.0

110

I

8195
8145

2672

30.48 15.85

24083
30899

1

16.201.48

2684

2077

136

17.205.43

30.48 15.85

9.14

0.588

23.0

110

2699

1483

1176

18.210.00

30.48 15.85

9.14

0.546

25.0

8125
8129

2717

1859

1162

19.215.19
20.235.61

30.48 15.85

9.14

0.504

35.05 18.29

10.67

0.744

21.237.14

35.05 18.29

10.67

22.239.58

35.05 18.29
35.05 18.29

25.252.99

35.05 18.29
35.05 18.29

1.147.22

10.180.44
II.

23.77 13.41

110

365+4
48299

I

27.0

110

31027

2

8149

2737

2154

1146

18.0

Ioo

31250

2

12445

3032

1910

1995

0.721

I9.0

100

1

10.67
Io. 67

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1973

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1958

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37.80 21.34

11.58

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37.80 21.34

11.58

0.747

19.0

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29.273.71

37.80 21.34

11.58

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2I. 0

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1899

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11.58

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30.278.59

37.80 21.34

11.58

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0.626

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2499

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3104

31.285.91

37.80 21.34
23.80 16.6o

11.58
8.20

0.590

32.177.10

0.628

33.212.44
34.206.30

30.48 16.46
28.90 16.50
27.40 16.20

9.14
9.50

23.242.32
24.246.89

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20.7

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IIO

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32.20 18.70

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-

41.268.38

32.16 19.51

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1990

3950

-

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32.26 24.15

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51360

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43.271.00

32.20 24.00

0.65C

59138

2

4280

0.615

140

24943

1

16385
3156

2864
997

543

1031
255

45.234.39

22.00 13.80
27.43 16.15 10.06

24.0
I8.0

135

44.135.00

10.96
8.45

0.640

23.0

Ito

-1

10058

2546

1050

93

Dimensions

in metres and weights

35.234.40
36.215.12

ship

in tonnes

no. 1-31 are not actual

byi 5t ships.

9473


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Weight in tonnes, \( E_{\text{MIN}} \) and \( E_{\text{MAX}} \) in m².
Fig. 6.1. E VERSUS STEELFACTOR K(STEELF)
ACTUAL SHIP DATA, & K.R. CHAPMAN DATA

STEEL FACTOR (CONSTANT)

ACTUAL STEEL WEIGHT

+ + + +

METHOD 4
STEEL WT.

+ + + +

E IN SQ. METRES

0.045
0.044
0.043
0.042
0.041
0.040
0.039
0.038
0.037
0.036
0.035
0.034
0.033
0.032
0.031
0.030
0.029
0.028
0.027
0.026
0.025
Fig. 6.2 ACTUAL STEEL WEIGHT VS SHAME'80 PLOT

REF. SHIP DG & CONST. - TAGGART (27)

ACTUAL STEEL WEIGHT

+ + + +

Taggart (27)

STEEL WEIGHT IN TONNES

L*(B+D)/100. IN SQ. METRES
The WS' is assumed to be at a standard fullness of 0.70 measured at 0.8D. Thus correction for steelweight for variation in Cb from 0.70 is made using the following two relationships

\[ WS_8 = WS' \left(1.0 + 0.5 \left( C_{bd} - 0.70 \right) \right) \] (tonnes)

where \( C_{bd} = C_b + (1.0 - C_b)(0.8 \times D - T)/3T \)

**METHOD 9:** This method is dated but mentioned here for completeness. It was used in the containership study by Scott (58) 1962, and was derived from standard freighters, taking into account the modifications, and reflecting the containerships built in that time, i.e. mostly converted ships.

**METHOD 10:** This method was developed by Carstens (59) 1970, and it was found that the unit area values of bulk carrier and container ships are in fact just about the same, with allowance for T/D corrections, since containerships have lower draft. The method is too detailed to apply for a study such as this, but is a good one-off type estimating method. No guidance is however given to adjust for use of higher tensile steel and its effect on steelweight. Further the method is applicable to ships of \( L \times B \times D < 100,000 \) m\(^3\) i.e. ships of Encounter Bay size 1500 Teu.

**Comparative Evaluation of Methods 1-8**

Steel estimating methods can be summarised broadly into four categories

(a) A method based on volume or cubic number
(b) A method based on area or surface numeral
(c) A method based on simple beam analogy
(d) A method based on classification rules.

In design studies, such as this, methods (c) and (d) are too detailed to be of much use. So basically methods (a) and (b) were preferred in earlier studies. However it has been found (35) that the steel weight is partly volume dependent, and partly dependent on section modulus. However estimating the factors suggested in (35) is beyond the scope of this study, due to the scarcity of data on actual steel weight.

The various methods can be categorised as follows:
Method 8 and Method 4 were adopted in this thesis. In Method 8, the designer inputs the steel weight factor (STEELF) to determine the steel weight whereas in Method 4, the steel weight is calculated automatically. The choice of method is given by using the controlling parameter ISTEEL = 1 for Method 8, and ISTEEL = 2 for Method 4.

The steel weights calculated by various methods are indicated in Table 6.4, the ratio of the difference between actual steel weight and the estimated weights divided by actual steel weight is shown in Table 6.5. The flush steel weight (FSTWT1) was validated with FSTWT2, as shown in Table 6.4, and found to be nearly 20% higher than FSTWT2 for data (1-32) but in closer agreement to data (32-45).

An analysis of different methods shows that Methods 1 and 2 underestimate the steel weight whereas Methods 3-7 overestimated the steel weight. As Table 6.6 is based on analysis of Table 6.5 indicates Method 4 has a mean percentage error of only 0.5% from actual steel weight, and standard deviation of 10%, hence both are within tolerable limits. Therefore Method 4 was used in the algorithm, with Method 8 left as an option for the user, since an estimating equation could not be established for the steel weight factor.
Table 6.4 Steel weight calculated by different methods

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All weights in tonnes.
Table 6.5 Difference from actual steel weight expressed as a fraction of actual steel weight.

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</tr>
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<td>0.118</td>
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<td>-0.089</td>
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<td>0.086</td>
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<td>0.021</td>
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<tr>
<td>21</td>
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<td>-0.013</td>
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<td>0.033</td>
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<tr>
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<td>-0.186</td>
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<td>-0.024</td>
<td>-0.014</td>
<td>0.015</td>
<td>0.005</td>
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<tr>
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<td>-0.190</td>
<td>0.060</td>
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<td>-0.044</td>
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<td>-0.007</td>
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<tr>
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<td>-0.060</td>
<td>-0.185</td>
<td>-0.148</td>
<td>-0.023</td>
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<td>28</td>
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<td>-0.051</td>
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<tr>
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<tr>
<td>30</td>
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<td>-0.157</td>
<td>-0.229</td>
<td>-0.190</td>
<td>-0.118</td>
</tr>
<tr>
<td>31</td>
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<td>32</td>
<td>-0.259</td>
<td>-0.407</td>
<td>-0.219</td>
<td>-0.169</td>
<td>0.005</td>
<td>0.019</td>
<td>-0.155</td>
</tr>
<tr>
<td>33</td>
<td>-0.025</td>
<td>-0.146</td>
<td>0.039</td>
<td>-0.012</td>
<td>0.108</td>
<td>0.129</td>
<td>0.008</td>
</tr>
<tr>
<td>34</td>
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<td>-0.040</td>
<td>0.113</td>
<td>0.078</td>
<td>0.210</td>
<td>0.228</td>
<td>0.095</td>
</tr>
<tr>
<td>35</td>
<td>0.062</td>
<td>-0.049</td>
<td>0.143</td>
<td>0.045</td>
<td>0.079</td>
<td>0.096</td>
<td>0.061</td>
</tr>
<tr>
<td>36</td>
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<td>0.019</td>
<td>0.164</td>
<td>0.115</td>
<td>0.230</td>
<td>0.250</td>
<td>0.135</td>
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<tr>
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<td>-0.372</td>
<td>-0.176</td>
<td>-0.148</td>
<td>0.119</td>
<td>0.150</td>
<td>-0.117</td>
</tr>
<tr>
<td>38</td>
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<td>-0.257</td>
<td>-0.075</td>
<td>-0.135</td>
<td>0.067</td>
<td>0.098</td>
<td>-0.104</td>
</tr>
<tr>
<td>39</td>
<td>-0.064</td>
<td>-0.189</td>
<td>0.008</td>
<td>-0.132</td>
<td>-0.038</td>
<td>-0.005</td>
<td>-0.100</td>
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<td>40</td>
<td>0.127</td>
<td>0.024</td>
<td>0.202</td>
<td>0.070</td>
<td>0.081</td>
<td>0.105</td>
<td>0.093</td>
</tr>
<tr>
<td>41</td>
<td>42</td>
<td>43</td>
<td>44</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 6.6. Analysis of steel wt. estimation methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Mean of Percentage Difference</th>
<th>Standard Deviation</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (WS1)</td>
<td>-5.43</td>
<td>1.060</td>
<td>1.097</td>
</tr>
<tr>
<td>2 (WS2)</td>
<td>-14.89</td>
<td>9.566</td>
<td>89.329</td>
</tr>
<tr>
<td>3 (WS3)</td>
<td>3.826</td>
<td>8.231</td>
<td>66.144</td>
</tr>
<tr>
<td>4 (WS4)</td>
<td>0.412</td>
<td>10.23</td>
<td>102.33</td>
</tr>
<tr>
<td>5 (WS5)</td>
<td>11.712</td>
<td>23.195</td>
<td>525.19</td>
</tr>
<tr>
<td>6 (WS6)</td>
<td>11.990</td>
<td>16.270</td>
<td>258.42</td>
</tr>
<tr>
<td>7 (WS7)</td>
<td>2.390</td>
<td>9.303</td>
<td>84.485</td>
</tr>
</tbody>
</table>
6.2. OUTFIT AND HULL ENGINEERING WEIGHT (WO)

Unlike steel weight, outfit weight determination may be simpler but due to the variety of items included in the outfit it is much more difficult to rationalise. There can be wide variation of the weight of outfit items recorded in two different shipyards because of the differences in accounting procedures, in respect of subcontracted jobs. It may be recorded as material cost or as labour cost. The best procedure at the preliminary design stage, is to ascertain the outfit weight from a basis ship item by item and proportion outfit weight in relation to the square number (L x B).

We consider here the various formulae suggested over the years for container ships, and then indicate the method used in this study. A comparative evaluation of the different methods is then carried out later in the section. The summary of equations used in different methods is shown in Table 6.7.

**METHOD 1:** The first formulation was given by Miller (52) 1970 and was based on an earlier work of Benford (5) 1965 on break-bulk ships. The assumption was that the container ship weight was less than that of a break bulk ship, and was ascertained by validation with existing data of first generation container ships, (conversion vessels mainly). The wood/outfit and hull engineering (WOHE1) was made a function of cubic number.

**METHOD 2:** Later in two studies on containership (53) 1973 and (54) 1972 the same formula as in Method 1 was used to estimate the wood/outfit and hull engineering weight (WOHE2).

**METHOD 3:** In a study on containership carried out by Chryssostomidis (37) in 1968 a formula specifically for containerships was suggested. Wood/outfit and hull engineering (WOHE3) was made a function of (L x B). 1.6

**METHOD 4:** The fourth formulation was given by Erichsen (39) 1971 and also used in a later study by Swift (55) 1972. The weight equation was like Method 1, derived from Benford's equation (51) 1965.
## TABLE 6.7. Summary of equations for wood/outfit and hull engineering weight.

<table>
<thead>
<tr>
<th>Method</th>
<th>Ship Type</th>
<th>Dimensions in feet</th>
<th>Dimensions in metres</th>
<th>Weight in long tons</th>
<th>Weight in tonnes</th>
<th>Ref. Yr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BB /C</td>
<td>WOHE1 = -0.71(CN/1000)^2 + 93.5 x (CN/1000) - 104</td>
<td>WOHE1 = -885.39 (CN/1000)^2 + 3302 (CN/1000) - 105.66</td>
<td>51 65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>BB /C</td>
<td>WOHE2 = WOHE1</td>
<td>WOHE2 = WOHE1</td>
<td>53 71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>WOHE3 = 0.15[(LxB)x0.986] /100</td>
<td>WOHE3 = 6.673 (LxB) /100</td>
<td>37 68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>GC /C</td>
<td>WO4 = 8.5 x (CNC/1800)^0.825 WHE4 = 53 x (CNC/1800)^0.825 WOHE4 = WO4 + WHE4</td>
<td>WO4 = 86.36 (CNC/1000)^0.825 WHE4 = 53.85 x (CNC/1000) x 0.825 WOHE4 = WO4 + WHE4</td>
<td>39 71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>A/C</td>
<td>WOHE5 = C01 x L x B</td>
<td>C01 = 0.32 for container ships</td>
<td>35 77</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>WOHE6 = C06 x L x B</td>
<td>C06 = 0.44 fitted equation</td>
<td>27 80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>C</td>
<td>BOFWT = (LxBxD)^0.425 SOFWT = (LxBxD/106)^0.65 HATWT = (L x B)^0.57</td>
<td>BOFWE = 4.62 x (LxBxD)^0.425 SOFWT = 10.31 x (LxBxD/106)^0.65 HATWT = 3.94 x (L x B)^0.57</td>
<td>46 69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>GC</td>
<td>WOHE7 = BOFWT + SOFWT + HATWT</td>
<td></td>
<td>61 74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>A</td>
<td>WOHE8 = C08 x L^1.3 x B^0.8 x D^0.3</td>
<td>C08 = 0.065 Katsoulis P.S. 35 77 (discussion)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>OC C</td>
<td>WOHE9 = C08 x L^1.3 x B^0.8 x D^0.3</td>
<td>C08 = 0.065 Katsoulis P.S. 35 77 (discussion)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Ship Type:** BB - Break bulk; C - Container; GC - General cargo; A - All ship type; OC - Ore carrier.
Benford's equation was subdivided into wood/outfit (WO4) weight and Hull engineering (WHE4),

\[ W_04 = c_0 \left( \frac{CN}{1000} \right)^{0.825} \text{ tons, and } W_{HE4} = c_{HE} \left( \frac{CN}{1000} \right)^{0.825} \text{ tons} \]

where \( CN = L \times B \times D / 100 \text{ ft}^3 \).

It was assumed that 23% of weight was for items not belonging to container ships, e.g. booms and fittings, riggings and blocks and refrigerated cargo insulation, and additional weights of hatch covers. Since containerships compared to ordinary dry cargo vessels have higher cubic displacement (CN/\( \Delta \)) ratio, the cubic number (CN) was replaced by a modified cubic number (CNC). The modified equation is

\[ W_04 = 85 \left( \frac{CNC}{1000} \right)^{0.825} \text{ tonnes, } W_{HE4} = 53 \left( \frac{CNC}{1000} \right)^{0.825} \text{ tonnes} \]

where \( CNC = 17.66 \times CN + 0.442 \times \Delta \text{ in m}^3, \Delta = \text{displacement in tonnes, } CN \text{ in m}^3 \).

METHOD 5: This method was adopted in the computer program, since it is the latest formulation available and reflects the current practice in container ship outfitting. The method is based on the square number (L x B), and shows that the outfit weight/(L x B), tonnes/m², for containership does not increase with increase in length of the ship. It is interesting to note that one of the co-authors in (60) 1962 gave the following equation for general cargo ships

\[ W_{OHE} = 0.36 \times (L \times B) \text{ tonnes} \]

This value of 0.36 when compared with 0.39 value given in (35) for general cargo ship corresponds to a 10% increase in outfit weight since 1962. And the outfit weight of container- ship does not vary with ship size as shown in Fig. 6.3, where outfit weight (WOHE5)/(L x B) plots as a horizontal line against length L. Similar conclusion is reached from another source (27) 1980 in Method 6.

METHOD 6: This method is also based on square number (L x B) and is given by a straight line, which was fitted to the curve given in (27) 1980.
Fig. 6.3. OUTFIT WEIGHT / (LENGTH*WIDTH)

REF. ACTUAL SHIP DATA

OUTFIT WEIGHT FACTOR T/SGM

0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20

OUTFIT WEIGHT FACTOR T/SGM

110 130 150 170 190 210 230 250 270 290

LENGTH BP IN METRES

ACTUAL SHIP DATA

Watson & Gilfillan'77

NAME DATA 1980

- - - - -
WOHE6 = 0.437 \times (L \times B) + 9.09  
(correlation 0.99 )

WOHE6 = 0.44 \times (L \times B) \text{ in tonnes}

The index 0.44 is higher than that suggested in Method 5 of 0.32 for containerships. This shows that the variability of outfit weight can be as much as 38% from one shipyard practice to another, in this case probably between American built ships which are heavier compared to European built ships plus demarcation differences.

**METHOD 7:** In this method, first proposed by Chapman (46) 1969 and also used in a later design study by Volker (61) 1974, the wood/outfit and hull engineering weight was subdivided into the following categories:-

(i) Bought in outfit material (BOFWT), all items bought in from outside suppliers fall into this category. All the major items fall into this category.
(ii) Shipyard outfit material (SOFWT), generally a fraction of the total weight and supplied by the shipyard.
(iii) Hatch cover weight (HATWT), generally supplied from outside as standard equipment. This method is considered here as a reference only, it gives very low outfit weight as shown in Table 6.8.

**METHODS 8 AND 9:** These equations were suggested by Katsoulis (35) 1977 for all types of ships. Since the value of K is a bit dated, some recently built container ship weight data were used to evaluate a new value of K. For containerships it was found that the block coefficient term can be dropped because the formula gave lower values of outfit weight compared to Method 9 or the actual weights. The value of K by Method 9 was found to lie between 0.0354 to 0.0714 with three values close to 0.065 as suggested by Katsoulis.

**METHOD 10:** This method (58) 1962 was developed prior to any purpose built container ships and is included to complete the analysis. It was assumed that the ore carrier outfit and Hull engineering (WOHE10) most closely approximates the weight of a containership and the formula is based on
Table 6.8 Outfit
methods
and Hull Engineering weights by different
Actual
WORE
WoHEI WOHE2 WOHE3 WOHE4 WORE. WOHE6 WOHE7 WOHE8 WOHE9
1.2287

2.2296
3.2312

4.2327
5.2435
6.2445
7.2461
8.2477
9.2513
Io. 2517
II.
2530
12.2546
13.2561
14.2668
15.2672
i6.2684
17.2699
18.2717
19.2737
20.3032
21.3038
22.3048
23.3059
24.3079
25.3108
26.3335
27.3340
28.3357
29.3375
30.3399
31.3437
32.1495
33.2699
34.2059
35.2050
36.2230
37.2150
38.2800
39.3300
40.3556
41.1990
42.
43.2864
44.997
45.2546

1250
I276
1319

1250
I276
1319

1940
2011
2129

1455
1460
1454

1119
I145
1187

1539
1574
1632

860
870
885

1024
I043
1067

1356
1759
1783
1824

1356
1759
1783
I824

2237
2770
2847
2977

1441
1897
1895
1881

1224
1399
1423
1463

1683
1924
1957
2012

899
997
1005
1019

1082
1352
1367
1384

1175
I210
1268
I;, 20
1537
1571
1629

1866
1931
1941
1974

1866
1931
1941
1974

3117
3342
3378
3498

1869
2130
2108
2084

1506
1573
1583
1618

2071
2163
2177
2225

1034
1056
1060
1071

1403
1596
1592
1601

1691
1790
1806
1857

2011
2047
2235
2245
2271
2300
2334
2371
2863
2869
2878
2888
2903
2922
2908
2899
2888
2869
2844
2801
1772
2409
2287
2372
2515
2475
2686
2897
2866
2945
2970
2927
I10o
2369

2011
2047
2235
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2271
2300
2334
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2863
2869
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2888
2903
2922
2908
2899
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2869
2844
2801
1772
2409
2287
2372
2515
2475
2686
2897
2866
2945
2970
2927
I100
2369

3638
3779
4598
4644
4771
4921
5098
5301
7663
7743
7871
8016
8259
8588

2063
2044
2542
2518
2480
2450
2426
2404
3833
3802
3731
3664
3626
3612

1658
1698
1920
1932
1965
2003
2048
2098
2642
2659
2687
2717
2769
2837

2280
2336
2640
2657
2702
2755
2816
2886
3633
3657
3694
3737
3807
3901

1085
1097
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I170
1179
1191
1204
1219
1410
1414
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1443
1460

1615
1627
1980
1975
1967
1983
1996
2011
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2932
2946
2984

1918
1978
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3365
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3559

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4806

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1206
1299
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1413
1462
1480
1541
798
1212

1387
2I07
1933
2222
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1810
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2865
3038
31o6
3467
860
2232

1595
2457
2268
2552
2548
2228
2709
3338
3413
3657
3531
3945
996
2551

Weight in tonnes.
127


an earlier study by Benford (62) 1958.

Comparative Evaluation of Methods 1-10

Actual wood/outfit and Hull engineering (AWOHE) of 45 containerships were compared with each of the above methods. The WOHE by each of these methods is indicated in Table 6.8. WOHE weights gave wide variation in weights by different methods. This wide variation is clearly indicated in Table 6.9 where, the percentage difference from actual WOHE weights as a ratio of AWOHE is indicated. Method 3 gave the worst results and was eliminated. Analysis of this percentage error is carried out in Table 6.10, where Method 9 gave the least percentage (mean) error.

Method 5 was, however, selected since it was felt that it reflects the trend in WOHE of recently built container ships.

A plot of outfit factor (OUFITF) defined as Actual wood/outfit and Hull engineering/(L x B) tonnes/m², Fig. 6.3, shows that the value of OUTFITF for containerships lie between 0.44 to 0.32, where OUTFITF = 0.44 as given by Method 6. The parametric study was carried out with OUTFITF = 0.32 as recommended by Method 5 (35)1977.

Moreover since the grouping of steel weight and outfit weight was taken as given in (35), Method 5 was adopted. The user can input any value to the outfit factor (OUFITF) in the program.

6.3. MACHINERY WEIGHT (WM)

The various types of machinery fitted and proposed for containerships include
- Direct drive slow speed diesels
- Geared medium speed diesels
- Geared steam turbines
- Geared gas turbines (a) Aero type (b) industrial type
- Nuclear power.

Factors which affect the choice of the type of machinery include: the specific weight, the space required, and the fuel consumption rate which often means that the weight is based
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Table 6.9 Difference in percentage from actual Outfit weight.
TABLE 6.10. Analysis of wood/outfit & hull eng. estimation methods.

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<td>9 (WOHE9)</td>
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on the sum of the machinery weight plus fuel weight for a given fuelling range. Naturally items such as reliability, the type of ship and cargo and the number of propellers may also be important.

Nuclear power has been discussed for containerships but the usual difficulties of acceptability in ports and high capital cost have prevented this plant being used so far.

Table 6.11 shows the distribution of the various types of machinery fitted on existing containerships. The increase in bunker fuel prices since 1973 had a significant effect on the choice of the main propulsion unit. This is well illustrated in Table 6.11 where 69% of newly built ships above 1000 Teu were equipped with steam turbine before 1974, compared to 37% after this date. Recent increases in oil prices, after 1979, had forced many shipowners to convert (63,64,65,66) existing ships with steam turbine installation to diesel propulsion. Medium speed propulsion has been confined to ship sizes less than 1000 Teu, due to their lighter weight and volume, Table 6.12. This advantage of higher cargo capacity is more than offset by lower specific fuel consumption of slow speed diesel, particularly for ship's size over 1000 Teu.

A summary of formulae for calculating the machinery weight, together with the machinery position, type of installation, for single or twin screw and the range of power for which it was developed is shown in Table 6.13. The machinery weight is subdivided into the main engine weight and the weights of auxiliaries. Each type of installation is discussed briefly and the weight equations selected in the algorithm is indicated.

---

**Direct drive slow speed diesel**

Most of the newly built containerships above 1000 TEU, after the oil price increases of 1973 and 1979 were installed with this type of engine as shown earlier, so in the program, all ships above 1000 Teu are assumed to have this type of installation. The various methods of estimating the weights are:

**METHOD 1:** This formula* 1, 2 was suggested by Watson in

---

*Note: Equations are mentioned in Table 6.13.
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Total                   | 162     |         |         |          |          |          |          |          |          |          |          |          |          | 276       |
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<th>KG/PS</th>
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<th>Weight in tonnes Eq.(10)</th>
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**NOTE:** In the case of steam turbine, it will be 10 kg/PS if reduction gears and condensers are included and for gas turbines reduction gears are not included.

<table>
<thead>
<tr>
<th>TYPE</th>
<th>SINGLE SCREW</th>
<th>TWIN SCREW</th>
<th>RANGE OF SHP x 10^3</th>
<th>MACHINERY POSITION</th>
<th>REF. NO.</th>
<th>YEAR</th>
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<td>BHP/10 + 200</td>
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<td>1.10</td>
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<td>Amidships Aft(-5%)</td>
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<tr>
<td></td>
<td>0.95(BHP/10 + 200)</td>
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<tr>
<td>C</td>
<td>4(BHP/100)+2.3</td>
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<td></td>
<td>WET 6.3(BHP/100)</td>
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<td>302(BHP/1000)^0.55</td>
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<tr>
<td>B</td>
<td>BHP(895-0.0025 x BHP)/10^4</td>
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<td>L</td>
<td>6.4(BHP/100)</td>
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<td>BARASS BHP/18 + 300</td>
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<td>9</td>
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<td>0.56(BHP)/0.70</td>
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<td>SHP/17 + 280</td>
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<td>1.10</td>
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<td>0.95(SHP/17+280)</td>
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<td>G &amp; C</td>
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<td>214 (SHP/1000)^0.5</td>
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<td>20</td>
<td>1.15</td>
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<td>TS 20</td>
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<tr>
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<td>WET 7.18(SHP)^0.495</td>
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<td>G</td>
<td>BARASS SHP/30 + 500</td>
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<td>A</td>
<td>WATSON 0.16(SHP)^0.89</td>
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<td>24</td>
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<td>Aft</td>
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<td>T</td>
<td>BUXTON 8.8(SHP)^0.5</td>
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TABLE 6.13 (Contd).

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<th>Type</th>
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<th>Range of SHP x 10^3</th>
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<td>26 12.2 1.386</td>
<td>15-120 Aft</td>
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<td>5.0(SHP)</td>
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<td>SS 0-15 Aft</td>
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<tr>
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<td>WET</td>
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<td>31 1.12</td>
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<td>180(BHP/1000)</td>
<td>0.57</td>
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**Ship Type**
- C - Container
- T - Tanker
- B - Bulk carrier
- G - General cargo
- A - All types
- L - Liner

*All formulae marked like this BHP or SHP is in metric horse power and weight in tonnes.*
1962 (60) for general cargo ships. The horsepower range was limited to 15000, highest possible during that period. Since that date there has been a reduction of main engine weight of 14%, and containerships with 120,000 h.p. are in operation. This method has been superceded by Method 7.

METHOD 2: These formulae 3,4,5 were developed for container ships by Erichsen in 1970 (39). It is applicable for both single and twin screw installation. It was later validated with existing containerships in another study by Swift in 1974 (55).

METHOD 3: This formula 6 used in a computer program for container ship design developed by Marad in 1973 (53) and compared to earlier formula had an index of SHP of 0.55 similar to that of steam turbine installation weight equation.

METHOD 4: This formula 7 was used in a bulk carrier preliminary design program in 1975 (48), but originally developed by Groeneweg & Polko 1971 (67) as a set of diagrams. The weight equation is for the mean line and used here for comparison only.

METHOD 5: This formula 8 was used in a cargo liner design program by Sen in 1978 (41) and is the same formula as used in earlier containership design study by Erichsen (39) and Swift (55) but the constant changed from 6.3 to 6.4 reflecting higher weight for cargo liners.

METHOD 6: This formula 9 was suggested by Barrass in 1977 (35) and was compared by Watson and Gilfillan (35) and found to give higher weights than formulae 10,11 because formula 9 is for ships with machinery amidships.

METHOD 7: This formula 10,11 is the latest available and suggested for all ship types by Watson & Gilfillan in 1977 (35). The total weight is broken into main engine weight and weight of auxiliaries. The formula is also applicable for medium speed diesel installation. A cross check with weights of some main engines both slow speed diesel as well as medium speed diesel is shown in Table 6.12. Equation 10 estimates the main engine weight quite accurately.
Comparative Evaluation of Methods 1-7

The formulae given in Table 6.13 for estimating the machinery weight is shown in Fig. 6.4. For the weights of auxiliaries two formulae were available Eq. 4 and Eq 11. Up to 40,000 hp the weight of auxiliaries estimated by Eq. 11 are greater than that by Eq. 4 and above 40,000 hp vice versa, and the difference is the same on either side of 40,000 hp. Eqs. 1 & 2 gave quite high specific weight/hp. Eq. 7 for bulk carriers lies above all other equations. Eqs. 5, 8, 9, 6 lie close to each other, with Eq. 6 giving overestimates at horse power less than 30,000 and underestimates at higher horse powers. Eq. 9 gives intermediate results between Eq. 6 and Eq. 5 & 8 at low powers.

A few points plotted for actual ships gave good agreement with Eq. 6. Eq. 10 & 11 was selected because it reflects the current practice and it is applicable for a wider range of horse power and r.p.m. as shown in Table 6.12. Also the auxiliary weight given by Eq. 11 is in close agreement with Eq. 4.

Medium Speed Diesel

Medium speed diesel engines have lower specific weight (see Table 6.12) and volume. Its lower engine height makes it an attractive mode of propulsion for RO-RO ships, because of the requirement of fore and aft access for trailer loading and unloading. As pointed out earlier, for higher power requirements the slow speed diesels have the advantage of lower fuel bills. Before the oil crisis of 1973, 10% of ships were equipped with this type of engine and this rose to 22% of the ships completed after 1974, as shown in Table 6.11. They are largely confined to ships of size less than 1000 Teu.

The formulae available for estimating the weight, Eq. 31 developed by Marad in 1973 (53) and the other developed by Volker in 1978 (61), shown in Table 6.13, was compared with Eq. 10 & 11 which was used in the program. These are shown in Fig. 6.5. The Eq. 10 & 11 gives lighter machinery weight than either Eq. 31 or Eq. 32, with equation 31 giving the heaviest machinery weight. The difference between eq. 32 from eq. 10 & 11 is between
Fig. 6.5. Machinery weight of Geared drive diesel plant.

Numbers on the curves refer to Equations in Table 6.I3.

- Eq.I0 & II
23% to 50%. Eq. 10 & 11 was used in the program because it gives fairly good main engine weight as shown in Table 6.12 and it is applicable for estimating both slow speed diesel and medium speed diesel weights.

Steam Turbine

The advantages of this simple rotary engine are considerable, particularly in the higher ranges of power, because of their very low specific weight (Table 6.12) and volume. Equally true is the benefit of having steam on board for auxiliary drives, heating and washing of tanks etc. Also in steam boilers the lowest grade (quality) of bunker fuel can be burned. However very few newly built ships are installed with this type of engine because of the relatively higher specific fuel consumption (200 gm/bhp-hr) compared to (140 gm/bhp-hr) of slow speed diesel engines. The quantity of fuel saved, rather than the difference in fuel quality is a decisive factor now. It is apparent from Table 6.11 that many shipowners were forced to change over to diesel propulsion after the oil crisis of 1973 and subsequently rises in fuel costs in 1979 even forced the shipowners to convert existing containerships with steam plant to diesel propulsion (63,64,65,66).

Various formulae have been suggested for estimating the weights of steam turbine plants since 1962 and are shown in Table 6.13. Of these many were derived from converted containerships. Each of these formulae are reviewed here, although steam turbine installation is not considered as an alternative propulsion plant.

METHOD 1: This formula 12,13 developed by Watson in 1962 (60), and subsequently updated eq. 27 by the author in (35) 1977, reflecting a decrease in weight of 48% for 15000 h p and the upper limit of the range increased from 15,000 in 1962 to 120,000 h p.

METHOD 2: This formulae eq. 14,15,16 (Table 6.13) was suggested by Benford in 1965 (51) for general cargo ships and was later modified for container ship studies by Erichsen (39) and Swift (55). These formulae are generally
of this form

$$WM = K \times SHP^{0.5} \quad \text{eq. 14 to 19}$$

Erichsen expanded the formula to include triple and quadruple screw configurations.

**METHOD 3:** This formula eq. 20 was developed by Miller in 1970 (52), and subsequently used in other containership studies by Marad in 1973 (53) and Hancock in 1972 (54). Eq. 20 gives machinery weight less than Method 2 for ships with machinery aft.

**METHOD 4:** This formula eq. 21 was developed by Chryssostomidis in 1968 (37) and derived from weights of converted container ships since the first purpose built containership came into operation in 1968, therefore eq. 21 gives higher machinery weights.

**METHOD 5:** This formula eq. 24 was given by Watson & Gilfillan in 1977 (35) for all ship types. Shp had an index of 0.89 unlike the equations previously suggested Eq. 14 to 21 , Eq. 23 , Eq. 25 and Eq. 28 . This was modified to reflect recently built ships and the index of Shp was given as 0.5, eq. 26 and eq. 27 as in Methods 2, 3 and 4.

An analysis of weights was not considered in the thesis, but validating the weight given by eq. 26 & 27 with some actual ship data gave good agreement. The user can easily introduce these equations in the program if steam installation is considered.

**Gas Turbines**

This type of installation has the highest fuel consumption (230 g/m/bhp-hr) and its performance is sensitive to fuel quality, thereby requiring costly grades of fuel. Its space and weight advantages, Table 6.12, do not compensate for the extra fuel costs. The failure of 'Euro liner' (68) one of the 4 ships installed with gas turbines have proved that they are not economical for merchant ships, although much better for naval ships, where design requirements are quite different.

Since only 4 ships have been built so far it is difficult to get a new formula. However Frankel (53) suggests two
formulae one for aero type eq. 29 and the other for industrial type eq. 30, the latter being 1 1/2 times heavier than the former. This type of installation is not considered in the program but like steam turbine equations, can be introduced by the user.

6.4. GUIDE WEIGHT (WG)

For estimating the guide weight (GWT) only one equation was available (46) 1970. This has been used subsequently in various containership studies without modification, (39,53,55). The guide weight is given by

\[ GWT = 0.713 \times CNT^{0.92} \text{ tons} \]  
Eq. 6.33

where CNT = Container capacity in Teu.

The container capacity of a ship is dependent on the stability and the operational requirements. And the container capacity of two ships of the same dimensions may be different. For this reason this equation can give misleading weights. Therefore it is suggested that the following form of the equation be adopted

\[ GWT = K \times CNT^{0.92} \text{ tons} \]

where guide weight (GWT) is made a function of hold container capacity, which is largely a function of the geometry of the ship, and thus constant for a ship of given dimensions. This assumption was checked against some actual ship data (Table 6.2) as shown in Table 6.14.

Ships 1-8 are older data probably based on conversion ships, and thus of heavier construction giving nearly twice the calculated guide weight of eq. 6.33. Ships 9-10-11 are of recent design and the actual weight is about 2/3 of the calculated weight.

Assuming that 2/3 of the containers are carried in the hold and the rest 1/3rd on the deck. It follows that guide weight can be made directly a function of the hold container capacity.

\[ GWT = 0.713 \times 1.016 \times CNT^{0.92} = 0.724 \times CNT^{0.92} \text{ tonnes} \]  
Eq. 6.34

or alternatively if the total capacity is only known then

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<td>774</td>
<td>963</td>
<td>522</td>
<td>1.84</td>
<td>366</td>
</tr>
<tr>
<td>3</td>
<td>1968</td>
<td>1-4</td>
<td>600</td>
<td>-</td>
<td>increase 512-540 guide wt.</td>
<td>256</td>
<td>2.00</td>
<td>180</td>
</tr>
<tr>
<td>4</td>
<td>1968</td>
<td>5-8</td>
<td>750</td>
<td>-</td>
<td>640-668 guide wt. for incr.</td>
<td>315</td>
<td>2.03</td>
<td>221</td>
</tr>
<tr>
<td>5</td>
<td>1968</td>
<td>9-13</td>
<td>1000</td>
<td>-</td>
<td>increase 910-944</td>
<td>410</td>
<td>2.22</td>
<td>288</td>
</tr>
<tr>
<td>6</td>
<td>1968</td>
<td>14-19</td>
<td>1250</td>
<td>-</td>
<td>1128-1180</td>
<td>504</td>
<td>2.23</td>
<td>353</td>
</tr>
<tr>
<td>8</td>
<td>1968</td>
<td>26-31</td>
<td>3000</td>
<td>-</td>
<td>3034-3102</td>
<td>1127</td>
<td>2.69</td>
<td>790</td>
</tr>
<tr>
<td>9</td>
<td>1980</td>
<td>32</td>
<td>928</td>
<td>612</td>
<td>268</td>
<td>383</td>
<td>0.699</td>
<td>268</td>
</tr>
<tr>
<td>10</td>
<td>1980</td>
<td>34</td>
<td>1336</td>
<td>746</td>
<td>357</td>
<td>535</td>
<td>0.666</td>
<td>375</td>
</tr>
<tr>
<td>11</td>
<td>1980</td>
<td>35</td>
<td>1712</td>
<td>1186</td>
<td>451</td>
<td>672</td>
<td>0.669</td>
<td>472</td>
</tr>
<tr>
<td>12</td>
<td>Under</td>
<td>43</td>
<td>3045</td>
<td>-</td>
<td>1031</td>
<td>1145</td>
<td>0.903</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>construction</td>
<td>44</td>
<td>550</td>
<td>-</td>
<td>255</td>
<td>236</td>
<td>1.080</td>
<td></td>
</tr>
</tbody>
</table>

Ship no. 1-31 not actual built ship.
The estimated weights by either of these equations is shown in Table 6.14.

However, checks against two ships 12-13 show that eq. 6.33 estimates the guide weight quite accurately. Therefore in the program eq. 6.33 is retained without modification until some more data are available to validate eq. 6.34 and eq. 6.35. Each of these equations are plotted in Fig. 6.6 together with some actual ship data.

## 6.5. CENTRE OF GRAVITY OF STEEL, OUTFIT, MACHINERY AND GUIDE WEIGHT

A literature search for equations for estimating the centre of gravity of steel, outfit, machinery and guide weight showed that there were very few methods available. Most were simple, relating the centre of gravity of weights to the depth of the ship, thereby neglecting the effect of fullness.

Various methods for estimating the centre of gravity (KG) of steel (KG_S), outfit (KG_OUT), machinery (KG_M/C) and guide (KG_GW) weights are indicated below, and a comparative evaluation is carried out. There were very few data points to validate the equations chosen in the program, so equations which gave reasonable results were selected. Table 6.15 summarises the formulae for estimating the centre of gravity of steel, outfit, machinery and guide weight.

### STEEL(FKGS)

Seven equations were available for estimating the centre of gravity of the steel weight, the equations are referred to as per Table 6.15.

**METHOD 1:** This equation 1 is the latest and specifically developed for containerships by Taggert in 1980 (27). As the ship size increases, the KG/D value decreases.

**METHOD 2:** This equation 3, 4, 5 was developed by Schneekluth in 1972 (56) for dry cargo vessels, taking into account the
Fig. 6.6. Guide weight versus container capacity.
<table>
<thead>
<tr>
<th>Eq. No.</th>
<th>Weight Item</th>
<th>Ship Type</th>
<th>Computer Nomenclature</th>
<th>Equations, all dimensions in metres</th>
<th>Author</th>
<th>Year</th>
<th>Ref. No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C</td>
<td>STLKG1</td>
<td>(0.725 - 0.0007218 × L) × D</td>
<td>Taggart</td>
<td>1980</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>BC</td>
<td>STLKG2</td>
<td>0.01 × D × (46.6 + 0.135 × (0.81 - CB)) x (L/D)^2 + (L/B - 6.5) × 0.008 D</td>
<td>Kupras</td>
<td>1975</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>GC</td>
<td>STLKG3</td>
<td>0.01 × D × (45.0 + 0.155 × (0.85 - CBD1)) x (L/D)^2 + (L/B - 6.5) × 0.008 D</td>
<td>Schneekluth</td>
<td>1972</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>GC</td>
<td>STLKG4</td>
<td>0.01 × D × (45.0 + 0.155 × (0.85 - CBD2)) x (L/D)^2 + (L/B - 6.5) × 0.008 D</td>
<td>Schneekluth</td>
<td>1972</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>GC</td>
<td>STLKG5</td>
<td>0.01 × D × (46.0 + 0.135 × (0.81 - CB)) x (L/D)^2 + (L/B - 6.5) × 0.008 D</td>
<td>Schneekluth</td>
<td>1972</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>STLKG6</td>
<td>0.61 × D</td>
<td>Chrysoostomidis</td>
<td>1968</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>C</td>
<td>STLKG7</td>
<td>0.64 × D</td>
<td>Scott</td>
<td>1962</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>C</td>
<td>WOKG1</td>
<td>(1.005 - 0.000689 × L) × D</td>
<td>Taggart</td>
<td>1980</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>BC</td>
<td>WOKG2</td>
<td>D + 1.25 for L ≤ 125.0</td>
<td>Kupras</td>
<td>1975</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D + 1.25 + 0.01 × (L - 125.0) for 125 &lt; L ≤ 250</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D + 2.5 for L &gt; 250.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>WOKG3</td>
<td>1.0 × D</td>
<td>Chrysoostomidis</td>
<td>1968</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>C</td>
<td>WMSKG1</td>
<td>0.47 × D (Steam turbine)</td>
<td>Taggart</td>
<td>1980</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>BC</td>
<td>WMDKG1</td>
<td>0.17 × T + 0.36 × D (Diesel)</td>
<td>Kupras</td>
<td>1975</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>C</td>
<td>WMSKG2</td>
<td>0.55 × D (Steam turbine)</td>
<td>Chrysoostomidis</td>
<td>1968</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Guides</td>
<td>GWTKG</td>
<td>0.65 × D</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C = Container ships; BC = Bulk carrier; GC = general cargo.
variation in type of construction, L/D ratio, block coefficient $C_b$ and L/B ratio. The formulae were validated with actual ships giving a deviation of $-0.5\%$ D and $+0.2\%$ D, and applicable for ships of length less than 180 m. Other values in equations are defined as follows:

$$D_1 = D + \frac{\text{sheer forward} + \text{sheer aft}}{7.0}$$

for parabolic sheer.

$$C_{BD1} = C_b + 0.25 (1 - C_b) \left(\frac{D-T}{T}\right)$$

ships with light framing

$$C_{BD2} = C_b + 0.5 (1 - C_b) \left(\frac{D-T}{T}\right)$$

ships with heavier framing

This equation was used in bulk carrier study by Kupras in 1975 (48), eqn 2, with minor modifications, the $D_1/D$ term was dropped from eq. 5. And for length of ship less than 120 m, steel centre of gravity was given by

$$STLKG_2 = STLKG_2 \text{Eq. 2) + } (1 - \left(\frac{L-60}{60}\right) \times 0.001 \times D \text{ m}$$

METHOD 3: These equations 6 and 7 were both developed for containership studies and are a bit dated. They relate the centre of gravity as a function of depth. The centre of gravity of the steel divided by the depth was plotted against the length of the ship for ships 1-45 (Table 6.2) for each of these methods, and shown in Fig. 6.7. Equations 2 to 5 show the same characteristics, with increasing size for a particular speed the KG/D values remains constant and the KG/D value increases with speed. The values of KG/D lie between 0.45 to 0.55. A check against 5 actual ship data gives the following KG/D values.

<table>
<thead>
<tr>
<th>Ship's Ref. No.</th>
<th>Actual KG/D</th>
<th>Calculated KG/D Eq. 1 Table 6.15</th>
<th>% Diff. in KG/D from actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>0.572</td>
<td>0.5697</td>
<td>0.40</td>
</tr>
<tr>
<td>33</td>
<td>0.590</td>
<td>0.5717</td>
<td>3.10</td>
</tr>
<tr>
<td>32</td>
<td>0.542</td>
<td>0.5972</td>
<td>-10.18</td>
</tr>
<tr>
<td>34</td>
<td>0.593</td>
<td>0.5761</td>
<td>2.85</td>
</tr>
<tr>
<td>35</td>
<td>0.648</td>
<td>0.5558</td>
<td>14.22</td>
</tr>
</tbody>
</table>
FIG. 6.7. KG. OF STEEL WT./D VS. LENGTH
REF. KUPRAS, CHRISOS., SCHNEKLUTH, SNARE (48, 37, 56, 27)

KG. OF STEEL WT./(T)/D/[M]

RATIO STEEL KG1/D

RATIO STEEL KG2/D

RATIO STEEL KG3/D

RATIO STEEL KG4/D

RATIO STEEL KG5/D

RATIO STEEL KG6/D

Ratio steel KG7/D

LENGTH BP IN METRES

0.70
0.69
0.68
0.67
0.66
0.65
0.64
0.63
0.62
0.61
0.60
0.59
0.58
0.57
0.56
0.55
0.54
0.53
0.52
0.51
0.50
0.49
0.48
0.47
0.46
0.45
0.44
0.43
0.42
0.41
0.40

110 130 150 170 190 210 230 250 270 290
Except for Ships 32 and 35, other ships are within ±5% of the equation 1. Eqns. 6 and 7 show good agreement with eqn. 1 for ships of length less than 170 m and Eqns. 2 to 5 show good agreement with eqn. 1 for ships of length greater than 250 m and speeds 25 to 27 knots.

Eqn. 1 was adopted in the program since it is the latest available and also it gives good agreement with the sparse data that was available.

**OUTFIT (FKGO)**

There were three equations available for estimating the outfit centre of gravity. These are summarised in Table 6.15 and described briefly.

**METHOD 1:** This equation 8, was developed specifically for containerships by Taggert in 1980 (27) and is similar to eq. 1 for the estimation of centre of gravity of steel. The centre of gravity of outfit weight divided by depth decreases as the length increases (see Fig. 6.8), though the rate of decrease as indicated by the slope is lower than that of Steel (Eq. 1).

**METHOD 2:** This formula 9 was developed by Kupras in 1975 (48) for a bulk carrier study and used here for comparison only. The centre of gravity of the outfit weight lies above the deck by this equation, from 1.2 m above deck for smaller ships to 2.5 m above deck for bigger ships.

**METHOD 3:** This formula 10 was developed for a containership study by Chryssostomidis in 1968 (37) and derived from converted containership and is a bit dated.

A comparative evaluation of these methods were carried out by plotting KG/D values against length of the ship and shown in Fig. 6.8. Eq. 9 gives the highest value with KG/D between 1.10 to 1.15 for ships of length 110 m to 300 m. Eq. 8 gives the lowest value with KG/D between 0.80 to 0.925. A check against three actual ship data shows that except ship No.41, which shows good agreement to Eq. 11, ships 36 and 33 gives results which overestimate by +5% of the eq. 8. Eq. 8 was included in the program to estimate the centre of gravity of wood/outfit and Hull
FIG. 6. KG. OF OUTFIT WT. / DEPTH VS. LENGTH

REF. KUPRAS, CHRISSOS, SCHNEEKLUH, SNAME (48, 37, 56, 27)

Taggert
RATIO OUTFIT
KG1/D
--- +++++--

Kupras
RATIO OUTFIT
KG2/D
***
1.000

Chryssostomidis
RATIO OUTFIT
KG3/D
0.975
0.950
0.925
0.900
0.875
0.850
0.825
0.800
0.775
0.750
0.725
0.700

KG. OUTFIT WT. [LT]/[D][M]

LENGTH BP IN METRES
engineering weight.

<table>
<thead>
<tr>
<th>Ship Ref. No.</th>
<th>Actual KG/D</th>
<th>Calculated KG/D Eq. 8</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 6.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>0.837</td>
<td>0.8567</td>
<td>+2.36</td>
</tr>
<tr>
<td>33</td>
<td>0.907</td>
<td>0.8586</td>
<td>+5.33</td>
</tr>
<tr>
<td>41</td>
<td>0.984</td>
<td>0.8201</td>
<td>+16.66</td>
</tr>
</tbody>
</table>

MACHINERY (FKGM)

Container ship studies (37, 39, 40, 52, 54, 55, 58) in the past had steam turbine installations and therefore the centre of gravity of diesel machinery installations was not considered. Three formulae were available one for diesel and two for steam turbine installations and these are discussed briefly.

METHOD 1: This eqn. 12 was proposed by Kupras in a bulk carrier study in 1975 (48) for slow speed diesels, where the centre of gravity of machinery weight was made a function of draft and depth of the ship.

METHOD 2: These equations were proposed for steam plant installations in container ship studies, eq. (11) by Taggert in 1980 (27) and eq. 13 by Chryssostomidis in 1968 (37). The centre of gravity was given as a function of depth.

The centre of gravity of machinery divided by the depth by these methods were plotted against the length of ship and shown in Fig. 6.9. A check was made against data for six ships with steam installations and as shown below.
Fig. 6.9. LENGTH BP VS KG MACHINERY/DEPTH

COMPARISON KUPRAS; SNAME; CHRIS SOTIMIDIS (48, 27, 37)

KUPRAS
DIESEL
++++

SNAME
TEAMTURBINE
-----

HRYSSOTIMI
TEAMTURBINE
--------

KG OF MACHINERY WT./DEPTH

0.60

0.55

0.50

0.45

0.40

130.0 150.0 170.0 190.0 210.0 230.0 250.0 270.0 290.0

LENGTH BP IN METRES
The above table shows that the ships with diesel installation will have centre of gravity of machinery lower than the ships with steam turbine plant. For steam turbine plant eq. 11 may be used, and for diesel engine eq. 12 is included in the program.

### CONTAINER GUIDES (FKGW)

There was no separate estimation method available for estimating the centre of gravity of the guide weight. Previous studies had either taken the guide weight as a part of the steel weight or outfit weight, and therefore no separate equations were developed. Centre of gravity of guide weight of 'Encounter Bay' was 10.72 m, which gives a centre of gravity/depth value of 0.65 (ship ref. No. 33, Table 6.2). Therefore in the program centre of gravity of container guide weight was taken as 65% of the depth of the ship.

### 6.6. LIGHT SHIP WEIGHT AND CENTRE OF GRAVITY (WTLT, FKGLTW)

The final item required to make up the light ship weight is the margin. And light ship weight = steel weight x allowance + outfit weight + machinery weight + guide weight + light ship weight margin.

Watson & Gilfillan (35) suggest an allowance for weld metal deposited and the rolling margin of 1% of the net
steel weight. This figure is adopted in the program. The purpose of the light ship weight margin is to ensure the attainment of a specified dead weight even if there is an underestimate of the light weight or an overestimate of the load displacement. Besides the light ship weight margin another margin to be considered is that of the centre of gravity. The margin on the centre of gravity is given because of the weight growth as the construction of the ship progresses, and later verified by carrying out the inclining experiment of the completed ship.

A detailed exposition of how the centre of gravity margin and the light ship weight margin can be reduced and their influence on the cost of construction is given by Gale (69) and the parametric study of various ship design margins is given by Hockberger (70, 71). Following are the indicative figures from the above studies.

Percentage growth figures which 50% of the past ships did not exceed.

<table>
<thead>
<tr>
<th>Margin Category</th>
<th>Preliminary Design</th>
<th>Detailed Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>10.9</td>
<td>2.6</td>
</tr>
<tr>
<td>Rise in CG</td>
<td>4.6</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Taggert (27) gives light ship weight margin of 3-6% of light ship height and a margin of +0.1 m to +0.3 m for rise in light ship weight centre of gravity. Watson & Gilfillan (35) recommends a light ship weight margin of 2% of light ship weight.

A check was made for some actual ship data on light ship weight margin.

Except Ships 43 and 45, all other ships have weight margin of about 2 to 3%. A weight margin of 3% of the light ship weight is therefore taken in the program. And a centre of gravity growth margin of +0.3 m is taken in the program. Therefore; Light ship weight = (steel weight x 1.01 + outfit weight + machinery weight + guide weight) x 1.03 tonnes

154
<table>
<thead>
<tr>
<th>Ref. Ship No.</th>
<th>Light ship weight</th>
<th>Light ship Wt. margin</th>
<th>% of light ship weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 6.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>15425</td>
<td>432</td>
<td>2.800</td>
</tr>
<tr>
<td>40</td>
<td>21844</td>
<td>508</td>
<td>2.326</td>
</tr>
<tr>
<td>32</td>
<td>7296</td>
<td>77</td>
<td>1.055</td>
</tr>
<tr>
<td>34</td>
<td>12762</td>
<td>427</td>
<td>3.345</td>
</tr>
<tr>
<td>-</td>
<td>14201</td>
<td>190</td>
<td>1.337</td>
</tr>
<tr>
<td>43</td>
<td>24560</td>
<td>1031</td>
<td>4.198</td>
</tr>
<tr>
<td>44</td>
<td>5020</td>
<td>69</td>
<td>1.375</td>
</tr>
<tr>
<td>45</td>
<td>14872</td>
<td>1125</td>
<td>8.184</td>
</tr>
<tr>
<td>33</td>
<td>14227</td>
<td>300</td>
<td>2.109</td>
</tr>
</tbody>
</table>

And light ship weight centre of gravity is given by

\[
FKGLTW = \left( WS \times FKGS + WO \times FKGO + WM \times FKGM + WG \times FKGW \right) / WTLT \ m
\]

\[
FKGLTW = FKGLTW + 0.3 \ m
\]

The light ship weight was then validated for actual ship data, Table 6.2. The light ship weight calculated by the program together with other weights and centre of gravity are shown in Table 6.16. The difference in light weight as a percentage of the actual light ship weight gives a mean error of -9.0% and standard deviation of 12.15% for 45 ship sample, which is within acceptable limits. There were 23 ships with diesel propulsion and 21 with steam plant in the sample. There were 7 ships with known light ship weight centre of gravity and following are the actual and calculated values.

<table>
<thead>
<tr>
<th>Ship Ref. No.</th>
<th>Actual Light ship CG (m)</th>
<th>Program Light ship CG (m)</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 6.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>10.08</td>
<td>10.59</td>
<td>-5.06</td>
</tr>
<tr>
<td>33</td>
<td>10.97</td>
<td>10.19</td>
<td>+7.11</td>
</tr>
<tr>
<td>34</td>
<td>10.18</td>
<td>10.26</td>
<td>-0.785</td>
</tr>
<tr>
<td>35</td>
<td>11.27</td>
<td>9.79</td>
<td>+13.13</td>
</tr>
<tr>
<td>36</td>
<td>10.38</td>
<td>10.59</td>
<td>-2.02</td>
</tr>
<tr>
<td>41</td>
<td>12.47</td>
<td>11.13</td>
<td>+10.75</td>
</tr>
<tr>
<td>42</td>
<td>13.97</td>
<td>14.03</td>
<td>-0.429</td>
</tr>
</tbody>
</table>

As seen from above the program gives reasonable results for both light ship weight and its centre of gravity.
Table 6.16. Weight and centre of gravity (actual versus calculated)

<table>
<thead>
<tr>
<th>Speed (knots)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>4550</td>
<td>4500</td>
<td>4450</td>
<td>4400</td>
<td>4350</td>
<td>4300</td>
<td>4250</td>
<td>4200</td>
<td>4150</td>
<td>4100</td>
</tr>
<tr>
<td>Desired</td>
<td>4550</td>
<td>4500</td>
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<td>4250</td>
<td>4200</td>
<td>4150</td>
<td>4100</td>
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</tbody>
</table>

% Diff. | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
CHAPTER 7
POWERING ESTIMATES

7.0. INTRODUCTION

7.1. STANDARDS OF SHIP PERFORMANCE

7.2. PROGRAM STRUCTURE

7.3. EFFECTIVE POWER ESTIMATES
   7.3.1. MOOR-SMALL METHOD
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7.5. SHAFT POWER VALIDATION
7.0 INTRODUCTION

The algorithm described in this chapter to calculate the installed horse power forms an important part of the total suite of programs. The method described here refers to containerships or fine hull forms but can easily be extended to incorporate all ship types.

Containership studies in the past have used one of the following methods of power prediction:
(a) A method based on regression analysis of trial and service horse power of existing ships and relating it to the main particulars of the ship e.g. Chapman (46) 1969.
(b) A method based on statistical analysis of full scale ships and models for prediction of various components of installed power i.e. effective horse power, delivered power, and various components of the propulsion e.g. propeller open water efficiency, wake, thrust deduction etc. e.g. Holtrop (72) 1977, (73) 1978.
(c) A method based on methodical series (e.g. series 60) for prediction of effective horse power Erichsen (39) 1971, Swift (55) 1974, and then application of method by Silverleaf (74) 1967 for prediction of propeller open water efficiency. Other propulsion factors are derived from empirical relationships to derive the delivered power.

In this thesis a different approach to the ones mentioned above have been adopted. This is based on deriving the effective horse power from average attainable performance of resistance by combining several methodical series. Up to this step the method adopted is similar to (c). The propeller open water efficiency is however derived from charts of propeller open water tests i.e. BP-6 charts of the Wageningen B-series. The diameter restrictions and the need to try various values of revolutions of propeller means that the propeller efficiency may depart from the optimum efficiency. Consequently these features and also the ability to relate propeller efficiency to a blade area ratio that is likely to be acceptable for cavitation are included in the program. Other propulsion factors are based on well-known empirical
relationships to derive the quasi propulsive coefficients, which in turn gives the delivered horse power. Further allowances such as shaft losses, service conditions and machinery derating are applied to derive the installed power.

Thus the program is not only able to give a first approximation to the installed power requirements, but also the characteristics of the propeller required to deliver this power.

The program is modular in nature and thus can readily be used for other studies e.g. parametric studies for changes in diameter, revolutions of the propeller, blade area ratio or propeller efficiency etc. The propeller design program can also be used on its own with effective horse power calculated by other methods.

The calculations within the program are in imperial units, and the input and output values are in metric units.

7.1 STANDARDS OF SHIP PERFORMANCE

A 'standard of performance' is defined as that level of performance for a given set of design parameters which would be estimated by a precise known method (75). And the simplest standard is the 'last design'. But even if the 'new design' performance is better than the 'last design' there is no guarantee that it is the best design. This notion as given by Moor (75) is introduced because at the estimation stage the designer has no idea of how the ship performs until real tests are carried out to evaluate the performance. Therefore the designer must have some standards based on past data against which he can judge if the ship is likely to give the performance for which it is designed. Performance standards for each of the elements of powering estimates are discussed briefly and those adopted for the program indicated. A detailed exposition of standards of ship performance is given by Moor (75) (1974).
RESISTANCE

Methodical series can be a good starting point as a standard of performance. But the methodical series do not ensure the best attainable performance. For predicting ship resistance, collation of a large amount of data on resistance of ships taken from many standard series results and plotting them as average attainable and optimum attainable level of performance seems reasonable. Such data was collected by Moor et al. both for single and twin screw ships (76, 77, 78) and forms the basis of prediction of resistance in this thesis.

PROPULSION FACTORS

The quality of resistance performance having been decided as above, the quality of propulsive performance is determined by that of the quasi propulsive coefficient. Simple relationships have been suggested for the prediction of quasi propulsive coefficients by Emerson (79) updated by Watson & Gilfillan (35), Lap (80) and Moor (81). However these relationships can be misleading since they do not take into account the effects of speed and fullness. It is more correct to break up the quasi propulsive coefficient and determine the constituent components of propeller open water efficiency, hull efficiency and relative rotative efficiency. Such an approach has been taken in this thesis.

(a) Propeller open water efficiency

While today many advanced propellers are designed against a theoretical background, the most suitable standard for assessment is the Wageningen-Troost B-series results at NSMB (82) and presented as regression equations in (83, 84). These computer faired data can be stored easily in a computer. In the program Wageningen B-series results for prediction of propeller open water efficiency given in the form of Bp-5 by Sabit (83) was used.
(b) **Hull efficiency and relative rotative efficiency**

The hull efficiency elements are usually determined for the methodical series and presented as regression lines e.g. BSRA Series, and as with resistance, the series values are particular to those series and not of any known standards. However, collation of random data are the best available for estimation of hull efficiency elements such as wake and thrust deduction and relative rotative efficiency was therefore calculated from Schoenherr's equations (84). A comparative evaluation of different equations developed for wake, thrust deduction can be found in Comstock (85) and Cameron (86). Cameron (86) recommends Schoenherr's equations because both single and twin screws propulsion factors can be calculated, and give reasonable results.

(c) **Ship model correlation**

Since all the standards mentioned so far apply to models in controlled conditions, these must be extrapolated to ships under trial conditions. The delivered power of the ship dhp, is then given by

\[ dhp = (l+x)_{\text{Froude}} \times \frac{EHP}{\eta_D} \text{ hp} \quad \text{Eq. 7.1} \]

where \((l+x)_{\text{Froude}}\) is the ship-model correlation factor. For single screw the interim standards as adopted by ITTC were developed by Scott (87). For twin screws the BTTP 1965 (88) has so far been used but is recommended by Moor (75) that they be superseded by data presented by Scott (89).

The various formulations for \((l+x)_{\text{Froude}}\) were plotted in Fig. 7.1 for single screw ships and in Fig. 7.2 for twin screw ships together with some actual published data on \((l+x)_{\text{Froude}}\).

As can be seen from Fig. 7.1 that Scott's (simplified) formula given by 8-8 mean trend line, lies close to the average hull condition and best trial condition of Moor line 3-3 and BTTP 65 line 3'-3'. Therefore Moor's line 3-3 for average hull condition and best trial condition was chosen, and is given by

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**Fig. 7.1.** Ship model correlation \((1+x)_{\text{Froude}}\) for Single Screw Ships.

<table>
<thead>
<tr>
<th>Hull condition</th>
<th>Trial condition</th>
</tr>
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<tbody>
<tr>
<td>(95)</td>
<td>(86)</td>
</tr>
<tr>
<td>1</td>
<td>Best ever achieved</td>
</tr>
<tr>
<td>2</td>
<td>Best</td>
</tr>
<tr>
<td>3</td>
<td>Best</td>
</tr>
<tr>
<td>4</td>
<td>Average</td>
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<tr>
<td>7</td>
<td>Average</td>
</tr>
<tr>
<td>8</td>
<td>Average</td>
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</table>

<table>
<thead>
<tr>
<th>Hull condition</th>
<th>Trial condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(95)</td>
<td>(86)</td>
</tr>
<tr>
<td>1</td>
<td>Best ever achieved</td>
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<tr>
<td>2</td>
<td>Best</td>
</tr>
<tr>
<td>3</td>
<td>Best</td>
</tr>
<tr>
<td>4</td>
<td>Average</td>
</tr>
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<td>5</td>
<td>Average</td>
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<td>Average</td>
</tr>
<tr>
<td>7</td>
<td>Average</td>
</tr>
<tr>
<td>8</td>
<td>Average</td>
</tr>
</tbody>
</table>
Fig. 7.2. Ship model correlation \((1+x)_{\text{fr}}\) for Twin Screw Ships.
\[ (1+x) \text{froude} = 0.367 + 2.5 \times L_{\text{BP(f)}}^{-0.25} + 27.5 L_{\text{BP(f)}}^{-1.0} \]

single screw Eq. 7.2

For twin screw, the Scott's data (mean line 3-3) plots as a straight line equation for average hull and average trial conditions. Since Scott's data is not accepted as a standard for twin screw ships, BTTP 1965 line of average hull condition and best trial condition was chosen in the program and given by

\[ (1+x) \text{froude} = 1.07 - 0.0002 \times L_{\text{BP(f)}} \]

twin screw Eq. 7.3

(d) Service margin

The service margin serves as an allowance for differences in the power requirements of a ship between its trial condition and its 'average' service condition. The standard practice is to adopt a service margin by adopting a fixed power margin, such that design speed is reached on trials at 80% of the normal power and this power margin is usually 25%. In the program the service margin was assumed to vary linearly from 15% at \( V/\sqrt{L} \) of 0.45 to 25% at \( V/\sqrt{L} \) of 1.05 as given by Cameron (86). Therefore the service margin (WEAIRA) over trial conditions is given by

\[ \text{WEAIRA} = 1.075 + 0.1667 \times \frac{V_{\text{knots}}}{\sqrt{L \, \text{ft}}} \]

Eq. 7.4

Swift (55) 1974 found that a container ship in the North Atlantic route, taking into account the voluntary and involuntary reductions in speeds due to seakeeping and also taking into account loss in speed due to hull deterioration due to fouling and corrosion requires a service margin of 18%. For the same ship Eq. 7.4 gives a value of 18.7% which is close to the above figure of 18%. Taggert (27) gives a value of 15% for large ships on relatively smooth-water routes to 35% service margin for smaller ships on the North Atlantic route, indicating a decrease in service margin as the length of the ship increases, as in Eq. 7.4.

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7.2. PROGRAM STRUCTURE

The calculation of the effective horse power and then the delivered and installed horse power is given by the flow chart in Appendix 1. Our objective is to select a propeller with maximum permissible diameter, highest propeller efficiency and lowest blade area ratio possible.

The whole program is subdivided into three parts, the main (MAIN) program containing the input, output and the CALL statements, effective horsepower calculation subroutine (EFECHP) and subroutine (POWER) to calculate the installed power and select the propeller. The program structure is shown in Fig. 7.3 together with the nature, size and the functions of the various programs in Table 7.1.

The various programs are now discussed below.

7.3. EFFECTIVE POWER ESTIMATION

A digital computer program for estimation of effective power is usually based on standard series results. However a choice must be made between true standard-series data where results are presented for a family of models varied in a logical manner and series which presents results of many model tests reduced to a logical presentation. The former group are generally difficult compared to the latter group for computerization and as pointed out earlier the latter group is to be preferred.

7.3.1. MOOR-SMALL METHOD (76)

This approach which falls into the second category was adopted in the program for computerization. Circular C values for ships of length 400 feet and standard values of corresponding draft and beam are presented in a tabular form as functions of block coefficient \( C_b \), speed length ratio \( V/\sqrt{L} \) and longitudinal centre of buoyancy position (LCB). First the actual ship is converted to a geosim of length 400 feet and appropriate tabulated \( C \) is obtained based on the particular values of \( C_b \), \( V/\sqrt{L} \) and LCB position.
FIG. 7.3. MAIN STRUCTURE OF THE POWERING PROGRAM

![Diagram of the powering program structure]

<table>
<thead>
<tr>
<th>NAME</th>
<th>ATTRIBUTE</th>
<th>OCCUPANCY SIZE (BYTES)</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAIN</td>
<td>PROGRAM</td>
<td>3245</td>
<td>Main program for READ, CALL and write statements. Used for validation of powering subroutine.</td>
</tr>
<tr>
<td>EFECCHP</td>
<td>SUBROUTINE</td>
<td>3210</td>
<td>Subroutine to calculate the effective horsepower, naked hull of the ship based on method of Moor &amp; Small.</td>
</tr>
<tr>
<td>POWER</td>
<td>SUBROUTINE</td>
<td>1950</td>
<td>Calculates the shaft horsepower and selects the best propeller based on Wageningen B-series 5 bladed propeller.</td>
</tr>
<tr>
<td>CAVIT</td>
<td>SUBROUTINE</td>
<td>530</td>
<td>Check for cavitation, for selection of minimum required blade area ratio based on Burrill's chart.</td>
</tr>
<tr>
<td>LAGINT</td>
<td>SUBROUTINE</td>
<td>212</td>
<td>Carries out lagrangian interpolation.</td>
</tr>
<tr>
<td>OVSLE1</td>
<td>FUNCTION</td>
<td>168</td>
<td>Circular values for ship of length from 30.48 m to 122 m.</td>
</tr>
<tr>
<td>OVSLE2</td>
<td>FUNCTION</td>
<td>134</td>
<td>Circular values for ship of length from 122 m to 365 m.</td>
</tr>
<tr>
<td>DENSMB</td>
<td>FUNCTION</td>
<td>266</td>
<td>Values of delta ($\delta$) on the optimum efficiency line.</td>
</tr>
<tr>
<td>EFNSMB</td>
<td>FUNCTION</td>
<td>266</td>
<td>Values of optimum efficiency ($\eta%$).</td>
</tr>
<tr>
<td>PRNSMB</td>
<td>FUNCTION</td>
<td>266</td>
<td>Values of pitch/diameter ratio on the optimum efficiency line.</td>
</tr>
<tr>
<td>POLONE</td>
<td>SUBROUTINE</td>
<td>156</td>
<td>Value of a polynomial by nested multiplication.</td>
</tr>
</tbody>
</table>

TABLE 7.1. ATTRIBUTES OF THE VARIOUS PROGRAMS.
This value of \( C \) is then corrected to the actual beam and draft by application of Mumford's indices (90, 76). Finally a skin friction correction is applied to correct for the ship's actual length to get the \( C \) value for the ship. The next subsection describes the program procedure in detail.

7.3.2. COMPUTER ALGORITHM

The optimum \( C \) values as given by Moor (78) for single screw ships and by Moor & Pattullo (77) for twin screw ships was stored as a two-dimensional array of \( C_b \) and \( V/\sqrt{L} \). It was assumed that the optimum \( C \) values and the best position of LCB are always attainable. The \( C \) values are tabulated for \( C_b \) values of 0.48 to 0.78 and \( V/\sqrt{L} \) of 0.40 to 1.5. Containerships usually have \( C_b \) in the range of 0.52 to 0.72 and \( V/\sqrt{L} \) 0.40 to 1.20 at partial to full load draft. Where the \( C \) for single screw (S.S.) and twin screw (T.S.) overlap, mean of the two values is taken to be the optimum attainable. The \( C \) values are for a standard ship of size 400' x 55' x 18'.

The input to the program are the length \( LBP \), beam (B), design draft (T), \( C_b \) and speed \( V \) and the output is the effective horse power of the ship. For the given value of \( C_b \) and \( V/\sqrt{L} \) the required value of circular \( C, C_m \) is calculated by interpolating first for \( C_b \) and then for \( V/\sqrt{L} \). The Lagrangian method of interpolation between three points is applied for this purpose in subroutine LAGINT.

The correction for deviation of beam and draft from the standard beam of 55' and draft of 18' is done by using the Mumford's Indices (76, 90). The value of the \( C_m \) after the beam correction is given by \( C_1 \), where

\[
C_1 = C_m \times \left( \frac{400}{LBP} \times \frac{B}{55} \right)^{-2/3} \quad \text{Eq. 7.5}
\]

And the value of \( C_1 \) after the draft correction is given by \( C_2 \), where

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where the value of $x = 0.90$ for $V/\sqrt{L} = 0.40$ to $1.10$ (78) and assumed to be the same at $V/\sqrt{L} = 0.40$ to $1.5$. A regression analysis of $(Y - 2/3)$ and $V/\sqrt{L}$ gives

$$ Y - 2/3 = 0.447 \times V/\sqrt{L_{ft}} - 0.360 \quad ; \text{(corr.} = 0.981) $$

Eq. 7.7

A skin friction correction is then applied for deviation of the length from the standard length of 400'. The tabulated values of circular $O$ versus length as given by Acevedo (91) was fitted by least squares method (50) and given by; for $100' < L < 400'$

$$ O = 0.11 - 0.39 \times 10^{-3} \times L + 0.24 \times 10^{-5}L^2 - 0.81 \times 10^{-8}L^3 $$

$$ + 0.14 \times 10^{-10}L^4 - 0.10 \times 10^{-13}L^5 $$

Eq. 7.8

and for $L > 400'$

$$ O = 0.85 \times 10^{-1} - 0.37 \times 10^{-4}L + 0.26 \times 10^{-7}L^2 - 0.75 \times 10^{-11}L^3 $$

Eq. 7.9

The wetted surface ($S$) is calculated by using Mumford's formula (76)

$$ S = 1.7 \times L \times T + C_b \times L \times B $$

Eq. 7.10

$$ S = \frac{0.0935 \times S}{\Delta^2/3} $$

Eq. 7.11

$$ L = 1.055 \times V/\sqrt{L} $$

Eq. 7.12

and $O$ correction = $O_0 - 0.0741$

Eq. 7.13

The skin friction correction correction (SFC) from eq. 7.11, 7.12, 7.13 is

$$ SFC = \frac{O \text{ correction} \times S}{L^{0.175}} $$

Eq. 7.14

Therefore the required value of circular $C$ from 7.6 and 7.14 is

$$ C = C_2 + SFC $$

Eq. 7.15

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And the effective horse power, \( EHP_N \) is then calculated from eq. 7.15

\[
EHP_N = \frac{C \times V^3 \times \Delta^{2/3}}{427.1} \text{ in H.P.} \quad \text{Eq. 7.16}
\]

7.4. PREDICTION OF DELIVERED POWER

Once the effective power of the ship is known, the power delivered to the propeller can be predicted by estimating the value of the quasi propulsive coefficient. The quasi propulsive coefficient as mentioned earlier is divided into its constituent parts and each of them is estimated separately.

Quasi propulsive coefficient \( \eta_D = \frac{EHP}{PD} = \eta_H \eta_R \eta_0 \) Eq. 7.17

and \( PD = \) delivered horsepower.

Where \( \eta_H \) is the hull efficiency, \( \eta_R \) is the relative rotative efficiency and \( \eta_0 \) is the propeller open water efficiency.

The hull efficiency is determined from the wake fraction \( (W) \) and thrust deduction fraction \( (t) \).

7.4.1. PROPELLER DESIGN BY Bp-S DIAGRAMS

The Wageningen-B series are usually used in the preliminary design stage to ascertain the propeller open water efficiency. The Wageningen-B series (82) are usually presented in the form of \( Bp-S \), \( Bu-S \) or \( K_T \), \( K_Q-J \) diagrams. Each type of presentation has its own advantages (92).

In most cases the nearest standard engine is selected, and the design problem is the choice of an optimum or near optimum propeller given the propeller rate of rotation, delivered power and advance velocity. In such a case the 'power approach' or 'marine engineer's approach' is adopted and use is made of \( Bp-S \) diagram.

The computer algorithm has been written with a view that the propeller open water efficiency can be other than optimum. Any propeller efficiency lying away from the optimum efficiency line \( \eta_{opt} \) in a \( Bp-S \) diagram is referred to as field efficiency \( \eta_0 \).
(a) **SELECTING THE PROPELLER RPM** (Revolutions per minute)

To obtain a highly efficient propeller, its RPM should be reasonably low. Since the standard engine is chosen, the propeller RPM is equivalent to the engine RPM in the case of direct drive diesel engines and in other cases the gear ratio of the reduction gear allows us to calculate the RPM. However to improve the propeller efficiency when the diameter is restricted, it is necessary to change the RPM. This can be done in the program by assigning the value 2 to the control parameter IREVLD otherwise a value of 1 is assigned.

(b) **SELECTING THE DIAMETER**

The propeller open water efficiency increases as the propeller diameter increases. Therefore it is logical to choose the maximum propeller diameter which fits the hull aperture after considering all clearances. To ensure enough head of water above the propeller tip such that the blades are completely immersed the diameter of the propeller is restricted to be 70% of the design draft. There are also manufacturing limitations on the largest possible diameter that can be cast. This is assumed to be 11.0 m.

(c) **SELECTING THE NUMBER OF SCREWS**

Single screws are more efficient than twin screws as far as the propeller efficiency is concerned. There are limitations on the amount of power that can be delivered through a single shaft. Therefore it is assumed that the maximum power that can be delivered through a single shaft is 50,000 hp. The program automatically chooses two shafts once this upper limit is reached.

(d) **SELECTING THE BLADE AREA RATIO**

Cavitation consideration govern the selection of appropriate value of Blade Area ratio (BAR). For maximum propeller efficiency the BAR must be as small as possible and cavitation considerations requires that the BAR must be above a minimum value. Therefore the program selects the
smallest value of BAR which also satisfies the cavitation criterion. The cavitation criterion was one given by Burill (93) as permissible upper limit of back cavitation. And the line representing $7\frac{1}{2}\%$ of back cavitation was thought to be acceptable.

(c) **SELECTING THE OPTIMUM EFFICIENCY**

The regression equations for the 4 and 5 bladed propellers published by Van Lammeren (82) 1969 and subsequently updated by Oosterveld (83) 1975 have been used to define the optimum efficiency lines.

For a given set of design parameters i.e. rate of rotation, speed of advance and delivered power i.e. $B_P$, to obtain the optimum efficiency and the corresponding values of $\delta$ and consequently the optimum diameter and pitch ratio Sabit (145) gives the regression equations of the form

$$\delta, \frac{P}{D}, \eta_{opt} = a_0 + a_1 \ln B_p + a_2 (\ln B_p)^2 + a_3 (\ln B_p)^3 + a_4 (\text{BAR}) + a_5 (\text{BAR})^2 + a_6 (\text{BAR})^3 + a_7 (\ln B_p)$$

\begin{align*}
&+ (\text{BAR}) + a_8 (\ln B_p)(\text{BAR})^2 + a_9 (\ln B_p)^2 (\text{BAR}) \\
\text{Eq. 7.18}
\end{align*}

Therefore for predetermined values of $B_p$ and BAR, the values of $\eta_{opt}$ is given by the subprogram EFNSMB and corresponding values of $\delta$ is given by the subprogram DENSMB and $P/D$ is given by the subprogram PRNSMB. The optimum efficiency lines have been defined for 5 bladed propellers in the program but can be changed to 4 simply by changing the values of the coefficients $a_0, \ldots, a_9$ in Eq. 7.18 from (83).

### 7.4.2. FIELD EFFICIENCY

In an earlier section it was mentioned that when diameter is restricted or when there is a need to try various values of RPM the propeller efficiency may no longer lie on the optimum efficiency line. In such cases it must be possible to determine the $\eta_0$. There are no established formulae for determining $\eta_0$, so a simple empirical relationship was established which gives the value of $\eta_0$ once the
value of $n_{opt}$ is known. For an assumed BAR, the BP is calculated from given values of delivered power, rate of rotation and the speed of advance. From subroutines EFNSMB, PRNSMB, DENSMB the values of $n_{opt}$, the P/D and the $\delta$ at that point can be calculated.

As shown in Fig. 7.4 the Bp- $\delta$ diagram was subdivided into grids. At a particular value of Bp a perpendicular line was erected which intersects the $n_{opt}$ line and the corresponding value of $\delta$ is read off. Next $n_0$ are read off at $\delta_{0.95}$ i.e. $\delta$ corresponding to optimum efficiency line $= 0.95$, $\delta_{0.90}$, $\delta_{0.85}$ and $\delta_{0.80}$ etc. This is repeated for more values of Bp until we get sufficient numbers of points to construct $\delta_{0.95}$ lines, and as shown in Fig. 7.4. Similarly for other BAR on a BP- $\delta$ diagram grids are constructed and the field efficiency ($n_0$) values read off. All these lines at $\delta_{0.95}$ to $\delta_{0.80}$ have characteristics of the $n_{opt}$ line.

Let value of delta at $n_{opt}$ be denoted by basic delta ($\delta_b$) and any other value delta as $\delta$, then knowing the values of $\delta_b$, $\delta$ and $n_{opt}$ the field efficiency ($n_0$) is given by

$$n_0 = n_{opt} - (1.5(1.0 - \frac{\delta}{\delta_b}) + 0.065) \times (1.0 - \frac{\delta}{\delta_b})$$

Eq. 7.19

A check was made between the values of $n_0$ calculated by Eq. 7.19 and those lifted from the graphs (82) and found to be in good agreement. Cameron (86) first used this expression for BAR = 0.60 and it was found that it is equally applicable for BAR of 0.75 and 1.05, as shown in Table 7.2. The $n_{opt}$ in Eq. 7.19 is defined for a particular BAR. The field efficiency $n_0$ can be derived for any value of BAR equal to 0.45 to 1.05 by Eq. 7.19.
Fig. 7.4. Determination of field efficiency from $B_p - \delta$ charts (open water test results of Wageningen $B$-screw series).
<table>
<thead>
<tr>
<th>Bar = 0.60</th>
<th>Delta (δ)</th>
<th>120</th>
<th>140</th>
<th>160</th>
<th>180</th>
<th>200</th>
<th>220</th>
<th>240</th>
<th>260</th>
<th>280</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ x 1.0</td>
<td>η opt</td>
<td>0.700</td>
<td>0.665</td>
<td>0.634</td>
<td>0.601</td>
<td>0.571</td>
<td>0.543</td>
<td>0.518</td>
<td>0.492</td>
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<td></td>
<td>η charts</td>
<td>0.696</td>
<td>0.660</td>
<td>0.627</td>
<td>0.595</td>
<td>0.563</td>
<td>0.535</td>
<td>0.510</td>
<td>0.486</td>
<td>0.46</td>
</tr>
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<td></td>
<td>η cal.</td>
<td>0.694</td>
<td>0.659</td>
<td>0.627</td>
<td>0.594</td>
<td>0.564</td>
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<td>0.474</td>
<td>0.450</td>
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<tr>
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<td>0.739</td>
<td>0.710</td>
<td>0.681</td>
<td>0.652</td>
<td>0.623</td>
<td>0.595</td>
<td>0.566</td>
<td>0.537</td>
</tr>
<tr>
<td></td>
<td>η cal.</td>
<td>0.765</td>
<td>0.737</td>
<td>0.710</td>
<td>0.681</td>
<td>0.652</td>
<td>0.623</td>
<td>0.595</td>
<td>0.566</td>
<td>0.537</td>
</tr>
</tbody>
</table>

Bar = 0.75

| δ x 1.0   | η opt    | 0.671 | 0.642 | 0.612 | 0.584 | 0.555 | 0.526 | 0.500 |
|           | η charts | 0.666 | 0.636 | 0.605 | 0.577 | 0.545 | 0.512 | 0.495 |
|           | η cal.   | 0.665 | 0.636 | 0.605 | 0.577 | 0.545 | 0.512 | 0.495 |
| δ x 0.95  | η charts | 0.658 | 0.620 | 0.590 | 0.560 | 0.532 | 0.505 | 0.480 |
|           | η cal    | 0.622 | 0.592 | 0.564 | 0.535 | 0.505 | 0.480 |
| δ x 0.90  | η charts | 0.565 | 0.538 | 0.571 | 0.543 | 0.514 | 0.484 | 0.460 |
|           | η cal    | 0.602 | 0.571 | 0.543 | 0.514 | 0.484 | 0.460 |
| δ x 0.85  | η charts | 0.481 | 0.460 | 0.435 | 0.410 | 0.385 | 0.365 | 0.345 |
|           | η cal    | 0.543 | 0.515 | 0.485 | 0.456 |

Bar = 1.05

| δ x 1.0   | η opt    | 0.645 | 0.615 | 0.585 | 0.555 | 0.523 | 0.495 | 0.469 | 0.445 |
|           | η charts | 0.639 | 0.610 | 0.580 | 0.549 | 0.517 | 0.490 | 0.464 | 0.440 |
|           | η cal    | 0.639 | 0.609 | 0.578 | 0.546 | 0.516 | 0.488 | 0.462 |
| δ x 0.95  | η charts | 0.621 | 0.591 | 0.562 | 0.532 | 0.503 | 0.476 | 0.450 | 0.426 |
|           | η cal    | 0.595 | 0.565 | 0.533 | 0.503 | 0.474 | 0.450 |
| δ x 0.90  | η charts | 0.538 | 0.511 | 0.484 | 0.457 | 0.432 | 0.410 | 0.385 | 0.365 |
|           | η cal    | 0.575 | 0.544 | 0.512 | 0.482 | 0.453 | 0.435 |
| δ x 0.85  | η charts | 0.489 | 0.459 | 0.432 | 0.408 | 0.385 | 0.365 | 0.345 |
|           | η cal    | 0.516 | 0.484 | 0.454 | 0.425 | 0.405 | 0.385 |

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### 7.4.3. Calculation of Wake, Thrust Deduction and Relative Rotative Efficiency (84, 86)

For single screw

\[
\text{Wake} = 0.1 + \frac{W_1}{W_2} x W_3
\]

where

\[
W_1 = \frac{4.5 x B x C_b^2}{L x C_W x C_m}
\]

\[
W_2 = \left(7.0 - 6 x \frac{C_b}{C_W}\right) \left(2.8 - 1.8 \frac{C_b}{C_m}\right)
\]

\[
W_3 = 0.5 \times (\text{dia.} \times \frac{0.625}{T} - 0.873 - \frac{\text{dia.}}{B})
\]

Thrust deduction = \(\text{wake} \times (0.5 + 0.4 \times (\frac{V}{\sqrt{L}} - 0.5))\)  

Relative rotative efficiency = 1.02

Eq. 7.21

Eq. 7.22

Twin screw

\[
\text{Wake} = 2 \times C_b^5(1.0 - C_b) + 0.2 \times 0.866^2 - 0.02
\]

Thrust deduction = 0.25 \times \text{wake} + 0.14  

Relative rotative efficiency = 0.985

Eq. 7.23

Eq. 7.24

Eq. 7.25

### 7.4.4. Design Procedure

The program accepts as input the speed (\(V\)), length (\(L\)), Beam (\(B\)), block coefficient (\(C_b\)), draft (\(T\)), the effective power (naked hull), the rate of rotation (RPM), and the control parameter IREVLD. The program logic is given by a flow chart of subroutine POWER in Appendix 1. The design problem can be formulated as; given the rate of rotation and the delivered power, to select a propeller of the largest possible diameter and the smallest blade area ratio with constraints on diameter, RPM and cavitation.

The design procedure for the choice of the appropriate propeller is iterative in nature. A certain value of quasi-propulsive coefficient is assumed to get the approximate
value of shaft horse power (SHP) from EHPN. The SHP is assumed to be 1.5 times the EHPN, an initial value of propeller efficiency of 0.1 and blade area ratio of 0.60. The initial approximation of SHP decides the number of propellers. A value of SHP higher than 50,000 hp is assumed to be delivered on twin shafts. The values of wake Eq. 7.20 or 7.23, thrust deduction Eq. 7.21 or 7.24, relative rotative efficiency Eq. 7.22 or 7.25 and $B_p$ are determined. The $B_p$ is constrained to lie between a value of 6 to 155 this being the range of the $\eta_{\text{opt}}$ line in a BP-$\delta$ diagram. The $\eta_{\text{opt}}$, Pitch-diameter ratio ($P/D_{\text{dia}}$) and the value of the $S_b$ is determined from the calculated value of $B_p$ and assumed BAR. From basic value of delta ($S_b$), the propeller diameter is calculated and given by

$$\text{propeller dia.} = S_b x \frac{V_a}{rpm} \quad \text{Eq. 7.26}$$

If the diameter is greater than either 0.70 x $T'$ or 28' than the lesser of the two values is taken as the new propeller diameter. In such a case the propeller efficiency obviously lies away from $\eta_{\text{opt}}$ line, therefore the value of $\delta$ is recalculated from the new diameter. The field efficiency $\eta_0$ is calculated from Eq. 7.19. If the propeller efficiency (PFNEW) is less than that assumed earlier, this is accepted as the correct value and the program then goes on to check for cavitation. However the initial value of propeller efficiency (PFBNEW) is kept at 0.1 so that absurd values of propeller efficiency are not calculated.

The value of quasi propulsive coefficient (QPC) is calculated with the value of PFNEW, hull efficiency and RRE and the new value of shaft horse power (SHPNEW) is calculated.

$$SHPNEW = \frac{EHPN}{\text{NOPROP}} \times CF \times \frac{\text{WEAIRA}}{\text{QPC}} \quad \text{H.P. Eq. 7.27}$$

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This value of Shp (SHPNEW) is compared to the initial value of the Shp which was calculated assuming \( \text{SHP} = 1.5 \times \text{EHP}_N \). If the difference in the two values of the shaft horse power is greater than 3\% of the SHP then the new value of Shp (SHPNEW) becomes the initial approximation to the shaft horse power and the whole procedure is repeated until the difference between successive values of shaft horse power is less than 3\%.

If the diameter restrictions exist, the only way to absorb the necessary power is to increase the RPM. The user can input through the control parameter \( \text{IREVLD} = 2 \) an increase in the RPM.

The propeller RPM is increased in steps of 15\% of the initial value and the last value of propeller efficiency (PFNEW) is taken as the starting point of the iteration and the value of \( B_p \) recalculated. When the successive values of the propeller efficiency are within 3\% of each other the iterations on RPM stop and the new value of the propeller efficiency and the RPM is output.

The cavitation check is made for the initial assumption on BAR. A 7\% back cavitation is accepted as the upper limit which gives an acceptable blade area ratio (DBAR). If the developed blade area ratio (DBAR) is less than that assumed initially the design is accepted. Otherwise the iteration is restarted with a new value of blade area ratio equal to DBAR. The acceptable range of blade area ratio is 0.45 to 1.05.

The machinery derating and the mechanical losses is assumed to be 10\% of the calculated power.

7.5. SHAFT POWER VALIDATION

To validate the horse power given by the program, over a wide range of ship size and speed, data from (57, 94) were taken. The ship size varies from 600 TEU to 3000 TEU and speed from 18 to 27 knots. As shown in Table 7.3, the shaft horse power calculated by the program and those from (57, 94) are in close agreement giving a mean error of 4.95\% and standard deviation of 8.07\%.
<table>
<thead>
<tr>
<th>Speed in Knots</th>
<th>18</th>
<th>19</th>
<th>21</th>
<th>23</th>
<th>25</th>
<th>27</th>
</tr>
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<tbody>
<tr>
<td>Container Capacity TEU</td>
<td>Ref. 57.94</td>
<td>Program</td>
<td>Ref. 57.94</td>
<td>Program</td>
<td>Ref. 57.94</td>
<td>Program</td>
</tr>
<tr>
<td>600</td>
<td>15100</td>
<td>13265</td>
<td>(12.15)</td>
<td>18000</td>
<td>15419</td>
<td>(14.34)</td>
</tr>
<tr>
<td>750</td>
<td>18000</td>
<td>15745</td>
<td>(12.53)</td>
<td>20600</td>
<td>18217</td>
<td>(11.56)</td>
</tr>
<tr>
<td>1000</td>
<td>18300</td>
<td>17598</td>
<td>(3.83)</td>
<td>21100</td>
<td>19093</td>
<td>(9.51)</td>
</tr>
<tr>
<td>1250</td>
<td>24083</td>
<td>22550</td>
<td>(6.36)</td>
<td>30000</td>
<td>28081</td>
<td>36545</td>
</tr>
<tr>
<td>1500</td>
<td>4004b</td>
<td>38273</td>
<td>(6.39)</td>
<td>40046</td>
<td>38273</td>
<td>(4.43)</td>
</tr>
<tr>
<td>1750</td>
<td>32000</td>
<td>41200</td>
<td>41410</td>
<td>49228</td>
<td>49424</td>
<td>(0.398)</td>
</tr>
<tr>
<td>2000</td>
<td>2250</td>
<td>31978x2</td>
<td>30648x2</td>
<td>39862x2</td>
<td>37536x2</td>
<td>48546x2</td>
</tr>
<tr>
<td>2500</td>
<td>32218x2</td>
<td>32054x2</td>
<td>41028x2</td>
<td>38351x2</td>
<td>48771x2</td>
<td>48441x2</td>
</tr>
<tr>
<td>2750</td>
<td>38500</td>
<td>49000</td>
<td>64436</td>
<td>64108</td>
<td>82056</td>
<td>76702</td>
</tr>
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</table>

Note: Figures in brackets indicate the % difference from actual, mean error = 4.95%, Std. Dev. = 8.07%, Variance 63.08.

Power in British horse power units.
CHAPTER 8

DEADWEIGHT AND CAPACITY ESTIMATES

8.0 INTRODUCTION

8.1 ROUND VOYAGE TIME

8.2 CARGO DEADWEIGHT ESTIMATE
   8.2.1. WEIGHT OF CREW & EFFECTS
   8.2.2. WEIGHT OF PROVISIONS & STORES
   8.2.3. WEIGHT OF FUEL
   8.2.4. WEIGHT OF BALLAST

8.3 CAPACITY ESTIMATES
8.0 INTRODUCTION

In the program the main dimensions L, B, T, D and $C_b$ are systematically varied to generate a number of designs which satisfy all the constraints. Since the displacement is known and the lightship weight can be calculated from these main dimensions, the deadweight of the ship can be ascertained. The deadweight is then apportioned into its constituent elements to estimate the cargo deadweight. Since most of the deadweight items like fuel, fresh water, stores are dependent on the time spent at sea and/or port an estimate of time spent at sea and port is required.

Once the weights of fuel, fresh water, stores have been estimated a check has to be made to ascertain if there is adequate space to carry these. Besides fuel and fresh water, containerships usually require some space to carry temporary/permanent ballast to improve the stability. The estimate of round voyage time, cargo deadweight estimate and the capacity estimates are discussed in turn.

8.1. ROUND VOYAGE TIME

The round voyage time is composed of

(a) Sea time for transiting the distance between each ports of call.

(b) Port time for berthing/unberthing and loading and unloading.

(c) Delays in port due to unforeseen circumstances.

Time at sea

In the program the time at sea (DAS) in days/round trip is calculated from the following equation

$$DAS = \frac{DIST}{24 \times V_s} \quad \text{in days}$$  \hspace{1cm} \text{Eq. (8.1)}

where $DIST =$ round trip distance between ports in nautical miles, and $V_s =$ service speed in knots.

Swift (55) introduces an approach where the 'expected speed' is determined taking into account the deterioration in speed with age due to hull fouling and corrosion, and loss in speed due to voluntary or involuntary speed reduction to maintain the seakeeping performance of the ship. Such
A model will require extensive data on the intended route and weather conditions.

Hancock (54) in a containership study takes into account the speed made good, inbound and outbound from Benford's (51) equation for speed increase or reduction due to change in deadweight. Frankel & Marcus (53) used the same equations for the containership model developed for MARAD (Maritime Administration).

Fortson (40) gives a similar type of expression for service speed reduction given the calm water design speed. Erichsen (39) takes a more simplistic view taking the speed loss of 3.5% of the service speed for containerships on the North Atlantic route.

However in this thesis a much more simplistic approach has been adopted. A service margin is included in the installed power so as to maintain the design speed under most weather conditions and also to take into account the deterioration in speed with age of the ship due to hull fouling and corrosion. The power service margin is given in Section 7.1 by Eq. (7.4).

**Time in port**

There are three basic approaches to estimating the time spent in port:

(a) Analytical methods

In this approach the container port facilities and operations is simulated by Queuing theory. UNCTAD (12), Novaes & Frankel (97) and Nehrling (98) employ such an approach for container ship and terminal simulation. However these models require extensive input data on terminal and ship operations.

(b) Methods based on average values

This is the usual method employed in most containership studies. The total time spent in port is composed of

(i) Time spent in berthing and unberthing of the ship.

(ii) Time spent in loading and unloading of containers.
(iii) Delays in port due to unforeseen circumstances, such as, waiting for an empty berth at a congested port, tidal variations in the approach channel, lower productivity due to inefficient use of resources.

Such an approach was adopted by Erichsen (39) and Hancock (54) in their containership study.

The time to berth/unberth a ship is usually taken as constant value, e.g. 3 hours/port of call (39). The time spent in loading and unloading containers is based on an average container handling rate of 12.5 - 25 lifts/hr (39, 54) and that the ship discharges all its cargo at that port (54) or a part of the cargo is discharged at port (39). This leads to the assumption that larger ships spend more time at port. Delays in port are taken as a constant value e.g. Erichsen (39) assumes 2 hours/port of call.

(c) Methods based on statistical analysis

The turnaround time in port is estimated by carrying out statistical analysis of actual port and ship data. Regression analysis is performed on actual data to investigate the relation between ship size, cargo loaded and unloaded and ship turnaround time in port. Edmond and Maggs (99) carried out such an analysis on data of 5 U.K. container terminals. Ross (100) carried out a similar analysis on a container terminal in Hong Kong.

It is difficult to develop any general formula which reflects the conditions at various ports. This is evident from the general conclusions reached by Edmond and Maggs (99) and Robinson (100). Whereas Robinson concludes that larger vessels turnaround more quickly than the smaller vessels, Edmond and Maggs conclude that turnaround time of container ships are extremely varied, and that there are no satisfactory simple linear relationships between the turnaround time and ship size or cargo handled.

Edmond and Maggs found that turnaround time can be predicted by the following equation

\[
\text{Turnaround time} = 17.5 + 0.0558 \times \text{number of containers handled} \text{ hours}
\]

\[
\text{Eq. (8.2)}
\]
And Eq. (8.2) gave reasonable values of the turnaround time compared to turnaround time as a function of ship size or handling rate. Therefore Eq. (8.2) was adopted in the program to calculate the time in port.

To calculate the number of containers handled in each port the method given by Edmond & Maggs (99) was adopted and is described below.

(a) The ship's container capacity in TEU was multiplied by the maximum load factor i.e. maximum of the outbound load factor (ALFO) or the inbound load factor (ALFI) and is given by

\[ ALFMAX = \text{maximum of } (ALFO, ALFI) \quad \text{Eq. (8.3)} \]

(b) The total number of containers handled (CONTHA) is

\[ CONTHA = CNT \times ALFMAX \times 4.0 \quad \text{TEU} \quad \text{Eq. (8.4)} \]

The factor 4.0 indicates that the containers are loaded and unloaded at each end of the sea leg, giving a factor of 2, and a further factor of 2 for the round voyage.

(c) Then the number of containers at each port of call (CONTHP) is

\[ CONTHP = \frac{CONTHA}{NPORT} \quad \text{TEU} \quad \text{Eq. (8.5)} \]

where the total number of ports NPORT = PORTD + PORTF, and is limited to 12.

PORTD = number of home ports
PORTF = number of foreign ports

(d) Then total number of days in port per voyage is

\[ DIP = \left(17.5 + 0.0558 \times \text{CONTHP} \right) \times \frac{(\text{PORTD} + \text{PORTF})}{24.0} + \text{DELAY} \quad \text{days} \quad \text{Eq. (8.6)} \]

where DELAY = delays in port which is input by the user. In the program no delay in port is assumed for the parametric study i.e. DELAY = 0.

**Round voyage time**

The round voyage time in days (RVYTIM) is calculated from Eq. (8.1) and Eq. (8.6) and is given by

\[ RVYTIM = DIP + DAS \quad \text{days} \quad \text{Eq. (8.7)} \]
The ship is assumed to be offhire for 15 days in a year for dry docking, general repairs, maintenance etc. Therefore the number of round trips/annum (RTPA) is

\[ \text{RTPA} = \frac{350}{\text{RVYTIM}} \] 

Eq. (8.8)

and days at sea per annum (DASPA) and days in port per annum are (DIPPA)

\[ \text{DASPA} = \text{DAS} \times \text{RTPA} \text{ days} \] 

Eq. (8.9)

\[ \text{DIPPA} = \text{DIP} \times \text{RTPA} \text{ days} \] 

Eq. (8.10)

The above calculations are carried out in the subroutine subprogram VOYTIM.

8.2. CARGO DEADWEIGHT ESTIMATES

The cargo deadweight is calculated by subtracting the light shipweight and the following items of deadweight from the displacement:

a) Weight of crew and effects
b) Weight of fresh water
c) Weight of stores and provisions
d) Weight of heavy fuel oil, diesel oil and lub. oil
e) Weight of ballast

and are estimated as described below.

8.2.1. Weight of crew and effects

The total number of officers (OFF), petty officers (PO) and crew (CREW) is input by the user, therefore total crew (TMAN) is

\[ \text{TMAN} = \text{OFF} + \text{PO} + \text{CREW} \]

and the weight of crew and effects (WTCREW) is given by

\[ \text{WTCREW} = \frac{\text{TMAN}}{6.0} \text{ tonnes} \] 

Eq. (8.11)

Eq. 8.11 was taken from Benford (51).

(b) Weight of fresh water

The weight of fresh water (WTFW) required is assumed to be 0.167 tonnes per man per day at sea (51)

\[ \text{WTFW} = 0.167 \times \text{TMAN} \times \text{DAS} \text{ tonnes} \] 

Eq. (8.12)
8.2.2. Weight of provisions and stores

The weight of provisions and stores (WTSTOR) is assumed to be 0.01 tonnes per man per day at sea (51)

\[
WTSTOR = 0.01 \times TMAN \times DAS \text{ tonnes Eq. (8.13)}
\]

The weight of crew and effects, weight of fresh water and the weight of provisions and stores is termed as the miscellaneous weight (WTMISC) and is given by

\[
WTMISC = WTCREW + WTFW + WTSTOR \text{ tonnes Eq. (8.14)}
\]

and the centre of gravity (FKGMX) of these miscellaneous weights is assumed to be (37, 106)

\[
FKGMX = 1.0 \times D \text{ m. Eq. (8.15)}
\]

These are calculated in the subroutine subprogram PAYLOAD.

8.2.3. Weight of fuel

The endurance (ENDUR) is assumed to be half the round voyage distance (DIST), but the user can specify as input other values of ENDUR.

Fuelling range (FRANGE) is given by

\[
FRANGE = \frac{ENDUR}{(240 \times V)}
\]

The procedure adopted is given by Buxton (101) and Femenia (102)

(i) Weight of fuel consumed at sea

Weight of main engine heavy fuel oil (WFMAIN) = SFC \times SHP \times 0.90 \times FRANGE \times 1.10 \times 24 \times 10^{-6} \text{ tonnes Eq. (8.16)}

Weight of auxiliary engine diesel oil (WDAUXS) = SFC \times AUXKW \times 1.34 \times \frac{0.5}{0.95} \times FRANGE \times 10^{-6} \text{ tonnes Eq. (8.17)}

Weight of main engine system luboil (WLSYS) = 0.26 \times SHP \times 0.90 \times 24.0 \times FRANGE \times 10^{-6} \text{ tonnes Eq. (8.18)}

Weight of main engine cylinder Luboil (WLCYLS) = 0.37 \times SHP \times 0.9 \times 24 \times FRANGE \times 10^{-6} \text{ tonnes Eq. (8.19)}
Total weight of Luboil consumed at sea \( (W_{TUBS}) = W_{LSYS} + W_{LCYLS} \) tonnes \( \text{Eq. (8.20)} \)

(ii) Weight of fuel consumed in port

Weight of auxiliary engine diesel oil \( (W_{DAUXP}) = SFC \times AUXKW \times \frac{0.75}{0.95} \times 24 \times DIP \times 10^{-6} \) tonnes \( \text{Eq. (8.21)} \)

Weight of auxiliary engine Luboil \( (W_{TLUBP}) = 1.29 \times AUXKW \times 1.341 \times \frac{0.75}{0.95} \times 24 \times DIP \times 10^{-6} \) tonnes \( \text{Eq. (8.22)} \)

(iii) Therefore total weight of heavy fuel oil \( (W_{TFUEL}) = W_{FMAIN} \) tonnes \( \text{Eq. (8.23)} \)

Weight of diesel oil \( (W_{DESL}) = W_{DAUXS} + W_{DAUXP} \) tonnes \( \text{Eq. (8.24)} \)

Weight of Luboil \( (W_{TUB}) = W_{TUBS} + W_{TLUBP} \) tonnes \( \text{Eq. (8.25)} \)

and the total weight of fuel \( (T_{TFUEL}) = W_{TFUEL} + W_{DESL} + W_{TUB} \) \( \text{Eq. (8.26)} \)

The following assumptions are made for calculating the weight of fuel.

(i) The main engine is a low speed direct drive diesel installation, continuous service rating is 90% of the maximum continuous rating, the specific fuel consumption is \( 162^{+} \text{gm/HP hr} \) (101) and carries a reserve fuel of 10% of the weight of fuel.

(ii) Auxiliary machinery is composed of two medium speed geared drive diesel with one of them as standby. The installed capacity of each of these generators \( (AUXKW) \) is 1500 KW. For refrigeration machinery the installed capacity would be higher and can be specified by the user as input. The auxiliary engine operates at 50% of the maximum continuous rating at sea and at 75% in port and the efficiency is 95% (102). The specific fuel consumption is \( 162 \text{ gm/HP.hr} \) (101).

(iii) The luboil consumption in port and at sea is calculated on the basis of the following specific fuel consumption

\[ \text{Recent improvement in specific fuel consumption has lowered this to 135.} \]
Auxiliary engine (in port) = 1.29 gm/HP.hr., Femenia (102)
Main engine cylinder (at sea) = 0.37 gm/HP.hr, Buxton (101)
Main engine system (at sea) = 0.26 gm/HP.hr, Buxton (101)

(iv) The main engine heavy fuel oil consumption in port is 24 tonnes/day and comes out of the reserve fuel (101).

The total fuel weight (TWFUEL) is calculated in the subroutine subprogram FEULWE.

8.2.4. Weight of ballast

Container ships must have adequate ballast capacity to improve their initial stability and hence increase their ability to carry more containers on deck. However carrying additional ballast means that the cargo deadweight capacity decreases, therefore average weight per container decreases, though the number of containers increases (see Section 13.2).

The user can specify if ballast is to be carried by assigning a value of 1 to the control parameter IBALAS. The amount of ballast is specified by giving a value to ABALAST, which is taken as a percentage of the total displacement.

The cargo dead weight (CDWT) is given by
\[
CDWT = DISPL - (WTCREW + WTFW + WTSTOR + TWFUEL + WTLT)
\]
tonnes Eq. (8.27)
and assuming homogeneous loading per container, weight of each container (WEC) = CDWT/CNT tonnes Eq. (8.28)
where DISPL = displacement of the ship tonnes Eq. (8.29)

8.3. CAPACITY ESTIMATES

The total volume capacity is generally divided into volume under the deck and volume above the deck. At the preliminary design stage while comparing alternative ship design only the former is estimated. The latter is usually required for general arrangement plans etc. The under deck volume capacity is subdivided into
(a) the hold volume (b) engine room volume (c) volume of peaks (d) volume of double bottom (e) volume of wing tanks (f) volume of deep tank, if any.
The estimation of under deck volume however requires knowledge of the hull form, which can either be derived from offsets or assuming a standard hull form. Kupras (48) uses volume coefficients of the whole ship, of the engine room and of double bottom, which are derived from series 60 hull form and block coefficient of 0.70 to 0.84. These volume coefficients are multiplied by the main dimensions of the ship e.g. L, B, T, D, Cb which are known at the preliminary design stage and corrections for camber, sheer, fore peak, cargo hatches, wing tanks are introduced using simple geometrical relationships. You and Rengyi (103) have developed similar volume coefficients for the BSRA series hull \(C_b = 0.65\) to \(0.80\) to represent medium V section hull form, and series 60 hull to represent ships with U section hull form (104). A simpler approach based on assuming a sectional area curve up to the upper deck is given by Cameron (86), and Watson & Gilfillan (35) give design charts for estimating the under deck volume based on main particulars only.

The volume of the machinery space can be deduced from Watson & Gilfillan (35), Cameron (86), Taggart (27), Sen (41), Kupras (48), You & Rengyi (103) for ships with various types of machinery installation. The volume of the peaks can be deduced from Sen (41), Kupras (48) and You & Rengyi (103). Wing tank spaces can be deduced from You & Rengyi (103). The volume of the double bottom can be deduced from You & Rengyi (103), Sen (41), Kupras (48), Lamb (105), Mandel & Leopold (106) or Chryssostomidis (37).

The hold volume is then calculated by subtracting the volume of the machinery space, peaks, double bottom and wing tanks. Assuming certain space losses, the number of containers in the hold can be estimated.

However in container ship studies, the hold capacity can be estimated easily by statistical analysis of under deck container capacity of existing containerships (see Section 13.2.1.). The length of the peaks are estimated
as a percentage of the $L_{BP}$, the machinery room length as a function of SHP (see Section 5.4), therefore only the volume of the double bottom and wing tank has to be estimated. This approach was preferred compared to the above approach because of the lack of good estimating equations for lower block coefficient.

Table 8.1 gives the actual capacity of wing tank spaces, double bottom spaces, fore peak spaces, miscellaneous tank spaces and settling tank spaces.

**Volume of double bottom**

The volume of the double bottom spaces ($VOLDB$) is given by (37)

$$VOLDB = L \times B \times DBHM \times C_b \times 0.69 \ m^3 \quad Eq. \ (8.30)$$

Table 8.2 shows the comparative evaluation of double bottom volume by different estimating equations together with double bottom volume of some actual ships (Table 8.1). All the equations gave good results, the equation developed by Chryssostomidis (37) was selected because it was used previously in a containership study.

The weight of fuel in double bottom ($WFDB$) is then

$$WFDB = VOLDB \times 0.95 \ \text{tonnes} \quad Eq. \ (8.31)$$

Assuming space lost due to framing etc., the stowage coefficient of fuel oil is 0.95 t/m$^3$.

The weight of fuel oil in settling tank was assumed to be 166 tonnes (106, 37). The rest of the fuel oil was assumed to be in the double bottom spaces. A check is made with the amount of oil that can be carried in the double bottom spaces (Eq. 8.31). If the space is insufficient, the rest of the fuel oil is carried in the wing tank spaces.

The centre of gravity ($FKGFB$) of the fuel oil/and ballast in double bottom spaces is given by (37, 106)

$$FKGFB = 0.67 \times DBHM \quad \text{m.} \quad Eq. \ (8.32)$$

and the centre of gravity ($FKGFD$) of the fuel oil in the settling tank is given by (37)
TABLE 8.1. Double bottom, wing tank, forepeak and aft peak capacities.

<table>
<thead>
<tr>
<th>Ship's Name</th>
<th>Double bottom capacity m³</th>
<th>Settling tank capacity m³</th>
<th>Wing tank capacity m³</th>
<th>After peak capacity m³</th>
<th>Fore peak capacity m³</th>
<th>Hold length m</th>
<th>Double bottom height (DBHM) m</th>
<th>Fore peak length m</th>
<th>Aft peak length m</th>
<th>Miscellaneous tank m³</th>
<th>Total capacity m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Colombus New Zealand</td>
<td>3226</td>
<td>313</td>
<td>5930</td>
<td>599+</td>
<td>121.693</td>
<td>1.8</td>
<td>9.186</td>
<td>12.2</td>
<td>-</td>
<td>-</td>
<td>10068</td>
</tr>
<tr>
<td>2. Euroliner</td>
<td>4154</td>
<td>763</td>
<td>9746</td>
<td>714</td>
<td>183.15</td>
<td>1.7</td>
<td>12.68</td>
<td>2.44</td>
<td>241</td>
<td>16344</td>
<td></td>
</tr>
<tr>
<td>3. Tokyo Bay</td>
<td>6495</td>
<td>985</td>
<td>10799</td>
<td>463</td>
<td>221.32</td>
<td>1.96</td>
<td>12</td>
<td>4.5</td>
<td>269</td>
<td>19828</td>
<td></td>
</tr>
<tr>
<td>4. Sealand Galloway</td>
<td>10758</td>
<td>1022</td>
<td>No wing tk2399</td>
<td>559</td>
<td>210.45</td>
<td>2.0</td>
<td>15.86</td>
<td>7.014</td>
<td>-</td>
<td>15338</td>
<td></td>
</tr>
<tr>
<td>5. Astronomer</td>
<td>2045</td>
<td>290</td>
<td>1824NA</td>
<td>-</td>
<td>-</td>
<td>1.7</td>
<td>-</td>
<td>-</td>
<td>233</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>6. C.P.Voyageur</td>
<td>2144</td>
<td>128</td>
<td>5088</td>
<td>295</td>
<td>102.33</td>
<td>1.35</td>
<td>12.95</td>
<td>7.32</td>
<td>181</td>
<td>7874</td>
<td></td>
</tr>
<tr>
<td>7. Encounter Bay</td>
<td>4048</td>
<td>195</td>
<td>4651</td>
<td>272</td>
<td>-</td>
<td>1.55</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9329</td>
<td></td>
</tr>
<tr>
<td>8. Selandia</td>
<td>7249</td>
<td>656</td>
<td>18789</td>
<td>-</td>
<td>200.16</td>
<td>1.70</td>
<td>18.47</td>
<td>4.8</td>
<td>518</td>
<td>27211</td>
<td></td>
</tr>
<tr>
<td>9. Taeping</td>
<td>7247</td>
<td>487</td>
<td>6254</td>
<td>575</td>
<td>-</td>
<td>1.55</td>
<td>-</td>
<td>-</td>
<td>93</td>
<td>15112</td>
<td></td>
</tr>
<tr>
<td>10. Oriental Class</td>
<td>3787</td>
<td>307</td>
<td>7320</td>
<td>614</td>
<td>130.98</td>
<td>2.0</td>
<td>14.70</td>
<td>8.62</td>
<td>336</td>
<td>12765</td>
<td></td>
</tr>
</tbody>
</table>
FKGFD = DBHM + 0.60 (D-DBHM) m Eq. (8.33)

Most of the parametric study is carried out for ships without temporary or permanent ballast. If some ballast is to be carried, to improve the ship's stability, it is assumed that the space remaining after providing adequate space for fuel can be used for ballast.
**TABLE 8.2.** Comparative evaluation of double bottom volume.

<table>
<thead>
<tr>
<th>Extent of double bottom (L-Lpp)</th>
<th>Lamb</th>
<th>(105)</th>
<th>Mandel &amp; Leopold (106)</th>
<th>Kupras (48)</th>
<th>Chrysostomidis (37)</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. 156.614</td>
<td>0.57</td>
<td>2471</td>
<td>160</td>
<td>0.372</td>
<td>3400</td>
</tr>
<tr>
<td>2. 209.84</td>
<td>0.60</td>
<td>3532</td>
<td>&quot;</td>
<td>0.409</td>
<td>4353</td>
</tr>
<tr>
<td>3. 257.62</td>
<td>0.654</td>
<td>6163</td>
<td>&quot;</td>
<td>0.476</td>
<td>7266</td>
</tr>
<tr>
<td>4. 245.50</td>
<td>0.585</td>
<td>4975</td>
<td>&quot;</td>
<td>0.434</td>
<td>6416</td>
</tr>
<tr>
<td>5. 173.79</td>
<td>0.684</td>
<td>3858</td>
<td>&quot;</td>
<td>0.496</td>
<td>4323</td>
</tr>
<tr>
<td>6. 132.73</td>
<td>0.717</td>
<td>2131</td>
<td>&quot;</td>
<td>0.507</td>
<td>2364</td>
</tr>
<tr>
<td>7. 192.02</td>
<td>0.660</td>
<td>3592</td>
<td>&quot;</td>
<td>0.471</td>
<td>4173</td>
</tr>
<tr>
<td>8. 234.33</td>
<td>0.594</td>
<td>4152</td>
<td>&quot;</td>
<td>0.429</td>
<td>5302</td>
</tr>
<tr>
<td>9. 172.80</td>
<td>0.624</td>
<td>2505</td>
<td>&quot;</td>
<td>0.433</td>
<td>3569</td>
</tr>
<tr>
<td>10. 168.48</td>
<td>0.684</td>
<td>3715</td>
<td>&quot;</td>
<td>0.487</td>
<td>4271</td>
</tr>
<tr>
<td>Author</td>
<td>Formula</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>-------------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lamb</td>
<td>$V = (L_{BP} - L_{pp}) \times B \times DBHM \times C_b \times K_3 \cdot m^3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mandel &amp; Leopold</td>
<td>$V = L_{BP} \times B \times D \times K_6 \times K_9 \times 0.69 \times C_b \cdot m^3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kupras</td>
<td>$V = L_{BP} \times B \times DBHM \times C_{BDB} \cdot m^3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chryssostomidis</td>
<td>$V = L_{BP} \times B \times DBHM \times C_b \times 0.69 \cdot m^3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

And $K_3 = 1.2 \cdot C_b - 0.06$, $L_{pp}$ = combined peak length in m.

$K_6 = 0.11$, $K_9 = 0.986$

$C_{BDB} = 2.068 \times \left(\frac{DBHM}{T}\right)^{0.5} - 1.5004 \times \left(\frac{DBHM}{T}\right) - 1.265 \times (0.70 - C_b)$
CHAPTER 9
SHIPBUILDING COSTS

9.0 INTRODUCTION

9.1. LABOUR COSTS

9.1.1. STEEL LABOUR MANHOURS & COSTS

9.1.2. OUTFIT LABOUR MANHOURS & COSTS

9.1.3. MACHINERY LABOUR COSTS

9.1.4. TOTAL LABOUR COSTS

9.2. MATERIAL COSTS

9.2.1. STEEL MATERIAL COSTS

9.2.2. OUTFIT MATERIAL COSTS

9.2.3. MACHINERY MATERIAL COSTS

9.3. MISCELLANEOUS ITEMS

9.4. TOTAL CAPITAL COST
9.0. INTRODUCTION

The cost estimation process can be categorised into the following three stages (107):
(a) Feasibility study (or preliminary or budget estimate)
(b) Design study (or detailed investigation)
(c) Fully detailed estimate

The first stage feasibility study or preliminary design study is what this thesis is concerned about. It is concerned with ranking different alternative ship designs on the basis of some merit criterion. At this stage absolute values are not that important but the cost must reflect the right magnitude of differences in the cost of alternatives.

The second stage is undertaken at a stage when a smaller number of alternatives, which are very near to the optimum design are compared.

In the third stage fully detailed estimate is carried out at tendering stage, when sufficient technical and economical data will be available for the proposed design. This type of study is usually undertaken by professional cost estimators who have recourse to considerable amounts of data on the same or similar designs. In this thesis we are concerned only with the first stage or feasibility study.

Usually in this type of study the cost grouping is
(i) Steel
(ii) Outfit and hull engineering
(iii) Machinery
These may be further categorised into
(a) Material   (b) Labour
(iv) Overheads and other expenses

The method adopted in this thesis is that developed by Carreyette (108) 1978 and the costs are at early 1980 level in pounds sterling and reflecting the cost of container-ship built in an average U.K. shipyard.

Wherever possible the data have been checked with other methods and the results show good agreement. Finally it is
shown that the model is quite simple to be updated.

First the labour costs are established, then the material costs and then the overheads, certain assumptions are made regarding profit to get the overall ship cost.

9.1. LABOUR COSTS

The labour costs can be subdivided as pointed out earlier into,

(i) Steel labour manhours and costs
(ii) Outfit labour manhours and costs
(iii) Machinery labour manhours and costs.

Total labour manhours are the basis of all direct labour costs, and once estimated, it is only necessary to apply wage rates prevailing in that year to get a fairly good estimation of labour costs. This is the approach adopted in this model, total manhours are validated with other methods and then the wage rates are applied to calculate the labour costs associated with steel, outfit and machinery respectively.

9.1.1. STEEL LABOUR MANHOURS AND COSTS

For the steel labour costs, the steel labour manhours were validated with another method, developed by K.R. Chapman (46) in 1970.

Steel labour manhours:

**Method 1**: This formula was suggested by Chapman (46), and the steel labour manhours (SWLMH1) is given by

\[ SWLMH1 = 1072 \times (GSTWT)^{0.71} \text{ hours} \quad \text{Eq. 9.1} \]

where GSTWT = Gross steel weight including forging and castings and scrap in tonnes.

The guide labour man hours (GWLMH1) is estimated separately, because it takes longer to fabricate and erect the guide structure

\[ GWLMH1 = 314.96 \times GWT \text{ hours} \quad \text{Eq. 9.2} \]
where \( GWT \) = weight of guide structure in tonnes.

Eq. 9.1 and Eq. 9.2 was used in containership study by Erichsen (39), Swift (55) and Volker (61).

**Method 2:** This formula was suggested by Carreyette (108) and is used in the computer program to estimate the steel labour manhours. The steel labour manhours from a variety of sources was related to the steel weight by the following relationship

\[
K = R_h C_b \left( \frac{W_s}{L_{BP}} \right)^{1/3} \quad \text{Eq. 9.3}
\]

where \( R_h \) = actual labour manhours per tonne of steel,
\( C_b \) = block coefficient at summer loaded draft,
\( W_s \) = Net steel weight in tonnes and
\( L_{BP} \) = Length bp in metres

\( K \) is constant for a shipyard but would vary between shipyards. Carreyette uses a value of \( K = 227 \), which he feels is high because of the mixed nature of type of ships, and gives a value of \( K = 180 \) for any shipyard building one-or-two types of ships.

Using \( K = 227 \) and rearranging equation (9.3)

\[
\text{Steel labour manhours } \text{SWLMH2} = R_h W_s = 227 \frac{W_s^{2/3} L_{BP}^{1/3}}{C_b} \text{ hours} \quad \text{Eq. 9.4}
\]

For ships with known steel weight and guide weight, the steel labour manhours was calculated by Method 1 and Method 2 and are as shown in Table 9.1. For Method 1 the guide labour manhour was calculated separately. It is not indicated in Method 2 that the guide labour manhours are included. Chapman's labour manhours were found to be less than Carreyette's labour manhours (see Table 9.1). Compared to a constant value of \( K = 227 \) as assumed in Method 2, Method 1 gives the value of \( K \) between 177 to 219, i.e. there is a variation of 3.5% to 22% in the steel labour manhours. Thus it is assumed that guide labour manhours can be included in the total steel labour manhours by including the weight of the guide structure in the net steel weight.
TABLE 9.1. Comparison of steel labour manhours.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1200</td>
<td>215.12</td>
<td>10446</td>
<td>0.558</td>
<td>485</td>
<td>756415</td>
<td>150350</td>
<td>906765</td>
<td>1164801</td>
<td>177</td>
</tr>
<tr>
<td>2</td>
<td>1512</td>
<td>212.44</td>
<td>8718</td>
<td>0.599</td>
<td>600</td>
<td>665275</td>
<td>186000</td>
<td>851275</td>
<td>957830</td>
<td>202</td>
</tr>
<tr>
<td>3</td>
<td>1600</td>
<td>185.00</td>
<td>6650</td>
<td>0.500</td>
<td>632</td>
<td>548920</td>
<td>195920</td>
<td>744840</td>
<td>916635</td>
<td>185</td>
</tr>
<tr>
<td>4</td>
<td>2000</td>
<td>215.00</td>
<td>5700</td>
<td>0.521</td>
<td>776</td>
<td>664300</td>
<td>240560</td>
<td>904860</td>
<td>1104106</td>
<td>186</td>
</tr>
<tr>
<td>5</td>
<td>2400</td>
<td>250.00</td>
<td>11500</td>
<td>0.538</td>
<td>918</td>
<td>809843</td>
<td>284580</td>
<td>1094423</td>
<td>1354218</td>
<td>183</td>
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<tr>
<td>6</td>
<td>1800</td>
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<td>14427</td>
<td>0.558</td>
<td>705</td>
<td>951307</td>
<td>218550</td>
<td>1169857</td>
<td>1536927</td>
<td>173</td>
</tr>
<tr>
<td>7</td>
<td>928</td>
<td>177.10</td>
<td>4629</td>
<td>0.628</td>
<td>383</td>
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<td>118730</td>
<td>543155</td>
<td>563806</td>
<td>219</td>
</tr>
<tr>
<td>8</td>
<td>1336</td>
<td>206.3</td>
<td>8761</td>
<td>0.587</td>
<td>535</td>
<td>667604</td>
<td>165850</td>
<td>833454</td>
<td>971082</td>
<td>195</td>
</tr>
<tr>
<td>9</td>
<td>1712</td>
<td>234.40</td>
<td>10058</td>
<td>0.631</td>
<td>672</td>
<td>736358</td>
<td>208320</td>
<td>944678</td>
<td>1033530</td>
<td>207</td>
</tr>
</tbody>
</table>

1. Guide Wt. = 0.713 x N^0.92 = GW
2. Steel labour MH = 1060 x W_S^0.71
3. Guide labour MH = 310 x GW
4. Steel labour MH = 227 x W_S^2/3, 1/3 / C_b
Indeed Carreyette in his paper mentions that the value of $K = 227$ is rather high due to the mixed nature of his sample of ship type, which includes small tugs to large bulk carriers, and that a shipyard specialising in building a few ship types will have a value of $K = 180$.

In the thesis it is assumed that the shipyard is not a specialist yard and therefore will have a value of $K = 227$.

**Steel labour costs**

To convert steelwork labour man-hours to total steel work labour costs, it is necessary to apply an average wage rate (reflecting both skilled and unskilled trade), overheads and profit. The 1980 average shipyard wage rate was £2.40/hour. This can be conveniently updated by using current wage rates published in (109). Fig. 9.1 shows the average hourly rate in shipbuilding industry since 1969, from £0.5768/hr in 1969 to £2.4/hr in 1980 - a four fold increase in eleven years.

Steel labour costs (CSL) is given by (108) from eq. (9.4)

$$\text{CSL} = \frac{A_1 \times W_s^{0.667} \times L^{0.334}}{C_b} \quad \text{£} \quad \text{Eq. (9.5)}$$

where $A_1$ is a constant which includes the wage rate, overhead, profit margin and the value of $K$. If $K = 227$, overheads are 100% and profit margins are 10% then

$$A_1 = 2.4 \times 227 \times 2.0 \times 1.10 = 1198.56 \quad \text{Eq. (9.6)}$$

The values of $A_1$ are plotted against this wage rate in £/hr for various overheads in Fig. 9.2. The value of $A_1$ can be given by the following equation, for different wage rates and overheads for $K = 227$ and profit margin of 10%.

$$A_1 = W_R \times (437.5 + 62.5 \times (0.4 \times \text{OVHEAD} - 3.0)) \quad \text{Eq. (9.7)}$$

where $W_R$ = average hourly wage rates in £/hour.

$\text{OVHEAD}$ = overheads and expressed as a percentage.

9.1.2. **OUTFIT LABOUR MANHOURS AND COSTS**

The outfit labour manhours was difficult to validate, since the shipyards vary in their accounting practices, e.g.
FIG 9.1 AVG. HOURLY EARNINGS SHIPBUILDING
REF. EMPLOYMENT GAZETTE

AVG. HOURLY WAGES £ /HR.

YEAR ENDING OCT.
Fig. 9.2. Steel labour cost constant $A_1$ for various values of wage rates and overheads (profit margin 10%).

Fig. 9.3. Outfit labour cost constant $C_1$ for various values of wage rates and overheads (profit margin 10%).
one shipyard may put the subcontracted items as labour costs and others as material costs. Therefore, outfit labour costs were validated.

Method 1: The first method calculates the outfit labour manhours and is from the same source as used for validating the steel labour manhours. Though developed in the early 1970's (46) it has found subsequent uses in (61) 1974, 1978 and other studies (53) 1973, (55) 1974.

The outfit labour manhours (OLMH1) is given by

\[ OLMH1 = 3493324 \times (L \times B \times D/10^6)^{0.60} \text{ hours} \] Eq. (9.8)

where \( L, B, D \) are in metres.

Method 2: Carreyette found that it is difficult to analyse outfit labour manhours since accountancy practice is to charge subcontracting labour to 'materials', that is, something 'bought in' and therefore not chargeable to the shipyard labour accounts. He found that outfit labour costs followed the same pattern as steel labour costs i.e.

\[ H = ax^n \] where \( H = \) total manhours, \( x = \) the size or quantity, \( a = \) a constant and \( n < 1 \).

The general form of the equation for estimating outfit labour cost (COL) is therefore given by

\[ COL = C_1 \times W_0^{2/3} \text{ £} \] Eq. (9.9)

\( COL = \) total cost of outfit labour, assuming no subcontracting

\( C_1 = \) factor which includes levels of productivity, wage rates, overheads and profit.

The value of \( C_1 \) and its variation with overhead and wage rates for a profit margin of 10% is shown in Fig. 9.3. The value of \( C_1 \) can be expressed by the following equation,

\[ C_1 = W_R \times (30.0 \times OVHEAD + 2937.5) + 50 \] Eq. (9.10)

where wage rate (WR) is assumed to be £2.4/hour (1980) and can be updated from Employment Gazette (109).

Table 9.2 gives the comparative outfit labour costs by Method 1 and Method 2. Chapman's outfit labour costs
TABLE 9.2. Comparison of outfit labour costs

<table>
<thead>
<tr>
<th>No.</th>
<th>TEU</th>
<th>L m.</th>
<th>B m.</th>
<th>D m.</th>
<th>Actual WO tonnes</th>
<th>Labour Man hrs.</th>
<th>Labour costs (£) (1)</th>
<th>Labour costs (£) (2)</th>
<th>Exclude Overhead (£) (3)</th>
<th>Diff. (1)-(3) (£) (4)</th>
<th>(1)-(3)</th>
<th>SHP</th>
<th>SHP 0.82</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1200</td>
<td>215.12</td>
<td>30.63</td>
<td>17.37</td>
<td>2230</td>
<td>951514</td>
<td>2283634</td>
<td>2440839</td>
<td>1211885</td>
<td>1071749</td>
<td>0.469</td>
<td>60000</td>
<td>8281</td>
</tr>
<tr>
<td>2</td>
<td>1512</td>
<td>212.44</td>
<td>30.48</td>
<td>16.46</td>
<td>2699</td>
<td>911690</td>
<td>2188057</td>
<td>2772073</td>
<td>1376343</td>
<td>811713</td>
<td>0.371</td>
<td>32450</td>
<td>5002</td>
</tr>
<tr>
<td>3</td>
<td>1600</td>
<td>185.00</td>
<td>32.20</td>
<td>18.70</td>
<td>2150</td>
<td>936182</td>
<td>2246837</td>
<td>2382109</td>
<td>1182726</td>
<td>1064111</td>
<td>0.474</td>
<td>42000</td>
<td>6181</td>
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<tr>
<td>4</td>
<td>2000</td>
<td>215.00</td>
<td>32.20</td>
<td>18.70</td>
<td>2800</td>
<td>1024519</td>
<td>2458848</td>
<td>2840805</td>
<td>1410469</td>
<td>1048378</td>
<td>0.426</td>
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<td>8281</td>
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<tr>
<td>5</td>
<td>2400</td>
<td>250.00</td>
<td>32.20</td>
<td>19.50</td>
<td>3300</td>
<td>1150104</td>
<td>2760250</td>
<td>3169655</td>
<td>1573744</td>
<td>1186505</td>
<td>0.430</td>
<td>60000</td>
<td>8281</td>
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<tr>
<td>6</td>
<td>1800</td>
<td>259.08</td>
<td>32.00</td>
<td>18.29</td>
<td>3556</td>
<td>1126464</td>
<td>2703514</td>
<td>3331531</td>
<td>1654116</td>
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<td>0.386</td>
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<td>7</td>
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<td>177.10</td>
<td>23.80</td>
<td>16.60</td>
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<td>708241</td>
<td>1699778</td>
<td>1839527</td>
<td>913331</td>
<td>786446</td>
<td>0.463</td>
<td>17500</td>
<td>3015</td>
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<td>8</td>
<td>1336</td>
<td>206.30</td>
<td>28.90</td>
<td>16.50</td>
<td>2059</td>
<td>868895</td>
<td>2085348</td>
<td>2314409</td>
<td>1149112</td>
<td>936235</td>
<td>0.449</td>
<td>32000</td>
<td>4946</td>
</tr>
<tr>
<td>9</td>
<td>1712</td>
<td>234.40</td>
<td>27.40</td>
<td>16.20</td>
<td>2050</td>
<td>898613</td>
<td>2156672</td>
<td>2307660</td>
<td>1145761</td>
<td>1010910</td>
<td>0.469</td>
<td>28500</td>
<td>4498</td>
</tr>
</tbody>
</table>

1. Labour rate £2.40/hr, W/O overhead; K.R. Chapman's
2. $C_1 = 14300$; OHEAD = 100%; Wage rate = £2.40/hr; Carreyette
3. $C_1 = (30.0 \times \text{OVERHEAD} + 2937.5) \times \text{WR} + 50.0$; PUT OVERHEAD = 0; $C_1 = 7100$; Carreyette

profit = 0%; $C_1 = 6454.5$;
excluding overheads and profit is equal to Carreyette's outfit labour costs including overheads and profit. If the overheads are neglected in Carreyette's method, the outfit labour costs are half of Chapman's outfit labour costs.

Another reason for the difference between Carreyette's and Chapman's outfit labour costs is because, Chapman does not consider the machinery labour costs separately but takes account of all the labour costs other than steel and outfit as miscellaneous labour costs. The miscellaneous cost \((46)\) is calculated as

\[
\text{Miscellaneous labour costs} = 16\% \times (\text{steel labour costs} + \text{outfit labour costs}) \quad £
\]

Eq. (9.11)

9.1.3. MACHINERY LABOUR COSTS

The recorded manhours for machinery installation suffers from the same drawbacks as that of outfit labour manhours i.e. since most of the work is subcontracted, it is recorded as 'material costs'. Therefore the machinery labour costs \((CML)\) is calculated directly from the equation given below (108)

\[
\text{CML} = F_1 \times \text{SHP}^{0.82} \quad £
\]

Eq. (9.12)

where \(\text{SHP} = \text{total installed horsepower in PS}\).

The value of \(F_1\) was calculated from the equation given below and shown in Fig. 9.4

\[
F_1 = (\text{OVHEAD} \times 1.125 + 117.92) \times WR
\]

Eq. (9.13)

The value of \(F_1\) can be updated by inputting the current wage rate in shipyards from Employment Gazette (109).

Chapman as pointed out earlier in Section 9.1.2 calculates the machinery labour costs as 16% of the steel and outfit labour costs.
Fig. 9.4. Machinery labour cost constant $F_1$ for various values of wage rates and overheads (Profit margin 10%).

Fig. 9.6. Steel material cost constant $B_1$ for various values of steel cost/tonne and wastage (Profit margin 10%).
9.1.4. TOTAL LABOUR COSTS

The total labour costs was validated by comparing the total manhours calculated by Chapman's method, which was updated to 1974 by Volker (61) and further updated to 1980 from Burness & Corlett (57). The outline of Chapman's method both for material cost estimation and labour cost estimation is shown in Table 9.4. Carreyette's method was updated in the program to reflect early 1980 costs.

A comparative evaluation of total labour costs as shown in Table 9.3 between the two methods indicates that except for one ship i.e. No.7 which is smaller than the others, Chapman's method underestimates by 18% the total labour costs. For a 1200 TEU ship Carreyette's method overestimates the total labour costs by about 14% compared to Chapman's total labour costs, but for the rest of the ships the difference is within ± 12%.

Carreyette's method was adopted in the program for its simplicity of updating. It is based on actual shipyard estimates and the accuracy reported is between ± 5%. As can be seen in Table 9.3, the difference between Chapman's total labour costs and Carreyette's is within ± 5% in certain cases.

9.2. MATERIAL COSTS

As for labour cost the material cost is also subdivided into three groups:

(a) steel material cost
(b) outfit material cost
(c) machinery material cost.

There were two methods available for cost estimation, one by Carreyette (108) 1978 and the other by Chapman (46) 1970. Carreyette's method used in the computer model was updated to reflect 1980 costs by referring to (110, 111) for cost of steel plates and angles and other materials from (112, 113). The material cost indices for shipbuilding material and equipment was hard to find but it was ascertained
TABLE 9.4. K.R. Chapman's capital cost model (46, 61, 57).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Weight</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Flush Steel Wt.</td>
<td>$FSW = 0.0007L \times XD^{0.37}$</td>
<td>1.76 £</td>
<td>0.71 £</td>
<td>0.4258 £</td>
</tr>
<tr>
<td>2) Deck House Wt.</td>
<td>$DW = 129.63xLXBXD/10^6$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3) Container guide Wt.</td>
<td>$GW = 0.713xN$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross Steel Weight</td>
<td>$NS = FSW + GW + DW$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Steel Weight</td>
<td>$WS = 1.17 \times GS$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Steel Material cost</td>
<td>$+CSM = WS \times steel £$</td>
<td>£45.5/ton</td>
<td>£100.48/ton</td>
<td>£205/tonne</td>
</tr>
<tr>
<td>2. Steel work</td>
<td>SM = 1060 \times (GS)^{0.71}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Steel labour cost</td>
<td>+CSL = WR \times (SM + GM)$</td>
<td>£0.5</td>
<td>£1.745/hr</td>
<td>£2.50/hr</td>
</tr>
<tr>
<td>3. Outfit material cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Brought in</td>
<td>$WOB = (LXBXD)^{0.425}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) Shipyard</td>
<td>$WOS = (LXBXD/10^6)^{0.65}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3) Hatch cover</td>
<td>$WHC = (LXB)^{0.57}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4) Total factor</td>
<td>$WOF = WOB + WOS + WHC$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Brought in</td>
<td>COMB = C1 \times WOB</td>
<td>650</td>
<td>1560</td>
<td>644</td>
</tr>
<tr>
<td>2) Shipyard</td>
<td>COMS = C2 \times WOS</td>
<td>149600</td>
<td>359040</td>
<td>152879</td>
</tr>
<tr>
<td>3) Hatch cover</td>
<td>COMH = C3 \times WHC</td>
<td>189</td>
<td>454</td>
<td>193</td>
</tr>
<tr>
<td>4) Outfit material cost</td>
<td>COM = COMB + COMS + COMH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outfit man hours</td>
<td>OL = 411600(LXBXD/10^6)^{0.60}</td>
<td>£0.5/hr</td>
<td>£1.745/hr</td>
<td>£2.50/hr</td>
</tr>
<tr>
<td>Outfit labour cost</td>
<td>+COL = WR \times OL</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1/2 = 0.4258 £ 1974 exchange rate
(3) updated from (1) by multiplying by General Index of Retail Prices = 2.2076

Mild steel £44.4/ton
High tensile £55-£57/ton
Avg. steel cost £236/ton

(2)/(1) = 1.022
(1.0055)^4 = 1.022 i.e. @ 0.55%/annum
(3)/(2) = 2.16
(1.137)^6 = 2.16 @ 13.7%/annum

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### TABLE 9.4 (Contd.)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Miscellaneous labour costs</td>
<td>+CML = 16% (CSL + COL)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Overheads &amp; charges</td>
<td>+OVHEAD = 50%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machinery weight</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Single screw geared two cycle steam turb.</td>
<td>WM = 200(SHP/1000)^0.57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Geared medium speed diesel</td>
<td>WM = 180(SHP/1000)^0.57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Machinery cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Steam plant</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A) Chapman SS ship, SHP 50,000</td>
<td>+ CMM = C4 × (SHP)^0.535</td>
<td>253600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS ship 30000 &lt; SHP &lt; 100000</td>
<td>CMM = C5 × (SHP)^0.527</td>
<td>315600</td>
<td>£37000</td>
<td></td>
</tr>
<tr>
<td>(B) Volker 50000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(C) Burness &amp; Corlett</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Medium speed diesel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CMM = C7 × (CSL + CSM + COM + COL + OVHEAD + CML)</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Automatic logging</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ CAL</td>
<td>110000/SHP</td>
<td>£112,411</td>
<td></td>
</tr>
<tr>
<td>9. Profit</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ PROFIT = C9 × (CSL + COM + COL + OVHEAD + CMM + CAL)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Total cost</td>
<td>1 + 2 + 3 + 4 + 5 + 6 + 7 + 8 + 9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** Dimensions L, B, D in feet, SHP in British horsepower and costs in £ sterling.
<table>
<thead>
<tr>
<th>No.</th>
<th>TEU</th>
<th>K.R. Chapman, 50% overhead, 0% profit</th>
<th>2. Carreyette, 50% overhead, 10% profit</th>
<th>0% profit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Steel labour costs (£)</td>
<td>Outfit labour costs (£)</td>
<td>Miscellaneous costs (£)</td>
</tr>
<tr>
<td>1</td>
<td>1200</td>
<td>2176236</td>
<td>2283634</td>
<td>713579</td>
</tr>
<tr>
<td>2</td>
<td>1512</td>
<td>2043060</td>
<td>2188057</td>
<td>675979</td>
</tr>
<tr>
<td>3</td>
<td>1600</td>
<td>1787616</td>
<td>2246837</td>
<td>645512</td>
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<td>4</td>
<td>2000</td>
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<td>2458848</td>
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<td>2760250</td>
<td>861898</td>
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<td>6</td>
<td>1800</td>
<td>2807656</td>
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<td>881787</td>
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<td>928</td>
<td>1303572</td>
<td>1699778</td>
<td>480536</td>
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<td>8</td>
<td>1336</td>
<td>2000289</td>
<td>2085348</td>
<td>653702</td>
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<td>9</td>
<td>1712</td>
<td>2267227</td>
<td>2156672</td>
<td>707824</td>
</tr>
</tbody>
</table>

1. Wage rate assumed = £2.4/hr.
2. Assumed wage rate including overhead 50%; profit 10% = 1.50 x 1.10 x 2.4 = £3.96/hr.
3. C_l = 10700, (30 x 50 + 2937.5) x 2.4 + 50.0 = 10700.
that structural steel wholesale price indices (112) were a good guideline and is shown in Fig. 9.5. For ships built elsewhere the indices published for material as well as labour in (113) provide a good guideline.

The material costs as given by Chapman (46) were updated to reflect 1980 costs and is shown in Table 9.4. The breakdown of the various elements of the material costs are also shown in Table 9.4. Chapman's method was used to validate the material costs given by Carreyette's method. Carreyette found that material costs showed similar characteristics as those obtained for the labour costs. Thus the general form of the equation is given by,

\[ \text{Material Cost} = a x^n \]

where \( a \) is a constant, \( x \) is the size or the quantity variable and \( n \) is the index, which is < 1. Further the material cost functions did not show the same degree of economy of scale in size or quantity increases as the labour cost functions (108). Steel labour costs, steel weight has an index of 0.667 compared to 1.0, for steel material costs. Outfit labour costs, outfit weight has an index of 0.667 compared to 0.95, for outfit material costs. And for machinery labour costs and material costs, the installed horse power has the same index of 0.82.

9.2.1. STEEL MATERIAL COST

The steel material cost (CSN) is given by the equation

\[ CSM = B_1 x WS \quad \text{Eq. (9.14)} \]

where \( B_1 \) is a constant reflecting the cost of steel/tonne and the scrap percentage. The values of \( B_1 \) for various values of cost of steel/tonne (STLCOS) and scrap percentage is shown in Fig. 9.6. The value of \( B_1 \) increases linearly as the value of STLCOS increases. For a fixed value of STLCOS, increase in scrap percentage increases the value of \( B_1 \). The value of \( B_1 \) can be estimated from the following equation

207
FIG 9.5. STRUC. STEEL WHOLESALE PRICE INDEX.

INDEX

1970=100
AS BASE

1975=100
AS BASE

YEAR ENDING DEC.
\[ B_1 = \text{STLCOS} \times 1.18 \times \left( \frac{\text{SCRAP} - 7.5}{100.0} + 1.0 \right) + 0.20 \]

Eq. (9.15)

\( \text{STLCOS} \) = Cost of steel material in £/tonne is taken from (110, 111). The average value of steel material (plates and sections) works out to be £214/tonne.

\( \text{SCRAP} \) = the scrap percentage or the wastage of material, and is calculated from the following 4th order polynomial of \( C_{bl} \) (35)

\[ \text{SCRAP} = S(1) + S(2) \times C_{bl} + S(3) \times C_{bl}^2 + S(4) \times C_{bl}^3 + S(5) \times C_{bl}^4 \%
\]

Eq. (9.16)

where \( C_{bl} \) = block coefficient at 0.80 of the depth of the ship and is estimated from Eq. (9.17)

\[ C_{bl} = C_b + (1 - C_b)(0.8D - T)/3T \]

Eq. (9.17)

where \( C_b \) = block coefficient at design draft

\( D \) = Depth of the ship at side in m.

\( T \) = Design draft of the vessel in m.

9.2.2. OUTFIT MATERIAL COST

Outfit material cost (COM) is calculated from the following equation

\[ \text{COM} = D_1 \times 0.95 \]

\( \text{COM} \) in £

Eq. (9.18)

\( D_1 \) is a constant which reflects the equipment costs from manufacturer's quotations. The value of \( D_1 \) since mid 1975 is shown in Fig. 9.7. The formula for calculating \( D_1 \) is given by

\[ D_1 = 1500.0 \times \text{material index}/100.0 \]

Eq. (9.19)

Mid 1975 was taken as the base year and value of Material Index is taken as 100. The values of \( D_1 \) given by Carreyette (108) are compared with those calculated by Eq. (9.19) and shown in Table 9.5. Since outfit material cost indices were not available, shipbuilding structural steel price index (112) was used. As Table 9.5 shows it gives fairly

+ other indices may be preferred.
Fig. 9.8. Machinery material cost constant, $g_1$

Fig. 9.7. Outfit material cost constant, $g_2$
TABLE 9.5. Comparative values of $D_1$ & $G_1$ and updated values as per Fig. 9.5.

<table>
<thead>
<tr>
<th>Year</th>
<th>$D_1$</th>
<th></th>
<th>$G_1$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Given</td>
<td>Calc.</td>
<td>Given</td>
<td>Calc.</td>
</tr>
<tr>
<td>6/75</td>
<td>1500</td>
<td>1500</td>
<td>735</td>
<td>735</td>
</tr>
<tr>
<td>6/76</td>
<td>1725</td>
<td>1724</td>
<td>845</td>
<td>845</td>
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<tr>
<td>6/77</td>
<td>2011</td>
<td>1989</td>
<td>980</td>
<td>975</td>
</tr>
<tr>
<td>1/78</td>
<td>-</td>
<td>2111</td>
<td>-</td>
<td>1034</td>
</tr>
<tr>
<td>1/79</td>
<td>-</td>
<td>2369</td>
<td>-</td>
<td>1161</td>
</tr>
<tr>
<td>1/80</td>
<td>-</td>
<td>2531</td>
<td>-</td>
<td>1240</td>
</tr>
</tbody>
</table>
good results for the limited points that were available.

9.2.3. MACHINERY MATERIAL COST

Machinery material costs are assumed to be for ships with diesel installation. The cost equation is not sensitive enough to show accurately the difference from other types of installation (108). Since other types of engine installation are not considered in the program, the cost of engine is calculated by the following equation

\[ C_{MM} = G_1 \times SHP^{0.82} \text{ £ Eq. (9.20)} \]

The value of \( G_1 \) since mid 1975 is shown in Fig. 9.8. The formula for calculating \( G_1 \) is given by

\[ G_1 = 735.0 \times \text{Material Indices/100.0 Eq. (9.21)} \]

The values of material indices as in Eq. (9.19). The values of \( G_1 \) calculated by Eq. 9.21 are shown in Table 9.5 and are found to be in good agreement with the limited data that was available.

9.3. MISCELLANEOUS ITEMS

The various other items which may be added to the cost equation are:-

(1) Application of higher tensile steel, where used may be adjusted by upgrading the value of \( B_1 \) in Eq. (9.14). The following mix of steel grades are assumed in the calculation of steel material cost; 75% to 85% of Grade A, remainder Grades B, E, AH, DH or EH as given by Carreyette (108).

(2) Where twin screw propulsion is assumed machinery material cost may be increased by multiplying Eq. (9.20) by 10% (108).

(3) If controllable pitch propeller is fitted, e.g. triple screw containerships have the centre line propeller of this kind, the cost of this item must be included separately. The cost difference between fixed and controllable pitch
propeller \( (S_C p) \) is given by (108)

\[
S_C p = 38200 Q_0^{1/2} \text{ \£} \quad \text{Eq. (9.22)}
\]

where \( Q_0 = \) overall torque = 0.728 \( \frac{\text{SHP}}{\text{RPM}} \) tonne metres

In the program it was assumed that even at higher powers twin screw installation will be sufficient, therefore no adjustment for controllable pitch propeller is included.

(4) The cost of thruster \( (C_T) \) is estimated by the following equation (108)

\[
C_T = 58000 + 42000 T \text{ \£} \quad \text{Eq. (9.23)}
\]

where \( T = \) thrust in tonnes.

Containerships are sometimes fitted with thrusters. But this cost item is not included in the program, since it forms a small fraction of the total cost.

(5) The cost of fin type of stabilisers \( (C_{ST}) \) is given by (108)

\[
C_{ST} = 400 \Delta^{3/4} \text{ \£} \quad \text{Eq. (9.24)}
\]

where \( \Delta = \) displacement in tonnes.

Containerships are sometimes fitted with either fin type stabilisers or flume tank system. This cost item is not included in the program. It is assumed that the containerships are not fitted with any stabilisers.

(6) Cost differences from diesel installation, as assumed in the program, can be calculated separately and added to Eq. (9.20). Some equations given for slow speed diesels, medium speed diesels and steam turbines, developed by Buxton (107) at 1977 cost levels are:

**Slow speed diesel**

machinery (material + labour) costs, \( C_{M} + C_{ML} = )

\[
2708 \times \text{SHP}^{0.75} \text{ \£} \quad \text{Eq. (9.25)}
\]

**Geared medium speed diesel**

\[
C_{M} + C_{ML} = 3752 \times \text{SHP}^{0.70} \text{ \£} \quad \text{Eq. (9.26)}
\]
TABLE 9.6. Outfit material cost comparison.

<table>
<thead>
<tr>
<th></th>
<th>K.R. Chapman (Symbols defined in Table 4)</th>
<th>Model (weight in tonnes)</th>
<th>Diff.</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WOB</td>
<td>WOS</td>
<td>WHC</td>
<td>COMB</td>
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<td>642</td>
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<td>582</td>
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<tr>
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<td>623</td>
<td>2.36</td>
<td>576</td>
<td>894005</td>
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<tr>
<td>3</td>
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<td>677</td>
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<td>598</td>
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<tr>
<td>5</td>
<td>735</td>
<td>3.044</td>
<td>652</td>
<td>1054725</td>
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<tr>
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<td>724</td>
<td>2.976</td>
<td>663</td>
<td>1038940</td>
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<td>7</td>
<td>521</td>
<td>1.80</td>
<td>451</td>
<td>747635</td>
</tr>
<tr>
<td>8</td>
<td>602</td>
<td>2.247</td>
<td>550</td>
<td>863870</td>
</tr>
<tr>
<td>9</td>
<td>617</td>
<td>2.33</td>
<td>574</td>
<td>885395</td>
</tr>
</tbody>
</table>
Geared steam turbine

\[ \text{CMM + CML} = 36865 \times \text{SHP}^{0.50} \ \text{£} \tag{9.27} \]

These when compared with Carreyette's CMM+CML figure give comparable results as shown below, and thus can be updated to reflect present cost levels and introduced in the program by the user.

<table>
<thead>
<tr>
<th>H.P. (metric)</th>
<th>Buxton £ x 10^6 (1977) costs</th>
<th>Carreyette £ x 10^6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>slow speed diesel</td>
<td>medium speed diesel</td>
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<tr>
<td>30,000</td>
<td>6.1718</td>
<td>5.1075</td>
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</table>

9.4. TOTAL CAPITAL COST

The total Capital Cost of the ship (BLDGCO) is therefore given by

\[ \text{BLDGCO} = \text{steel labour cost} + \text{steel material cost} + \text{outfit labour cost} + \text{outfit material cost} + \text{machinery labour cost} + \text{machinery material cost} \ \text{£} \tag{9.28} \]

\[ \Rightarrow \text{BLDGCO} = A_1 \frac{\bar{w}_s^{2/3} L_1^{1/3}}{C_b} + B_1 \frac{\bar{w}_s}{C_1 W_0^{2/3}} + D_1 W_0^{0.95} + F_1 \text{SHP}^{0.82} \tag{9.29} \]

A 10% profit margin is included in the factors \( A_1, B_1, C_1, D_1, F_1 \) and \( G_1 \). In the program the user can specify any profit margin (PROFIT in percentage) and the capital cost is then given by

\[ \text{BLDGCO} = \text{BLDGCO Eq. (9.29)} \times \left( \frac{100 + \text{PROFIT}}{110} \right) \ \text{£} \tag{9.30} \]

Other factors such as overhead (as percentage), labour wage rate/hr., steel cost £/tonne and material indices for a particular shipyard and year may be input by the user.

Cost derived from the program is meant to indicate how much money a shipyard will pay for shipyard labour and
materials and overheads and also make some fixed profit. Price however is influenced by various factors such as market conditions, competition, number of vessels on order of the same type, interest rates, loan, subsidies and numerous other factors. So to validate the results given by the program, published prices of ships cannot be a good indication. This is evident from Fig. 9.9 where the cost of a standard Fairplay container ship of 1200 TEU was plotted against actual ship prices published in various journals. The 1200 TEU fairplay container ship cost was calculated without the set of containers as £/TEU and as shown in Table 9.7. Actual ship prices were converted in £ from the quoted figure with the average exchange rate in that year and the price was converted into £/TEU. Until the oil crises of 1973 the ship cost/TEU was less than the price/TEU, after that the ship price/TEU has always been less than the cost/TEU except for some ships. This is mainly due to the depressed shipbuilding market, heavy subsidies by the national government to shipyards, liberal credit terms to shipowners and other political factors, such as decision by various governments to keep the shipyards open at any costs brought about a fierce competition for shipbuilding orders.

The capital cost of the ship was thus validated with data from another source (57) for ships of 600 TEU to 3000 TEU and speeds of 18 to 27 knots. The same assumptions were made in the program as those in deriving the cost of ships in (57) and are indicated in Table 9.8 together with the actual cost of the ships and those calculated by the program.

The general trend and magnitude of the cost figures for 1980 seems to be of the right order. A cross check with the Fairplay 1200 TEU ship which costs £25.64 x 10^6 with a 1250 TEU ship of 23 knots (shown in Table 9.8) by the program gives a cost difference of 3.8%, which is within the accuracy of the ±5% quoted by Carreyette (108) for this method.

Table 9.7 shows that there was dramatic increase in the shipbuilding costs after the oil price rise of 1973-74, of about 110% and the escalation has been less than 5% per annum.
Fig. 9.3. CONTAINER SHIP PRICE VS. YEAR OF ORDER


Price in Pounds (U.K.)/TEU

Actual Ships Prices

1200 TEU Ship Fairplay

Year of Placement of Order
TABLE 9.7. Fairplay standard container ship prices.
25,000 DWT, 1200 TEU, 22 Knots, 9 Cylinder Sulzer, 30,100 BHP,
15% service margin, 85% MCR, Aux. 4 x 1000 KW Diesel Engine
Alternators.

<table>
<thead>
<tr>
<th>Year</th>
<th>Price of ship + 1 set containers</th>
<th>Price of one dry container</th>
<th>Price of one reefer container</th>
<th>Price of 800 dry containers</th>
<th>Price of 400 reefer containers</th>
<th>Price of 1200 TEU ship</th>
<th>% price escalation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>4.0</td>
<td>450</td>
<td>890</td>
<td>0.36</td>
<td>0.356</td>
<td>3.284</td>
<td>+5.968</td>
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<tr>
<td>1969</td>
<td>4.4</td>
<td>600</td>
<td>1100</td>
<td>0.48</td>
<td>0.440</td>
<td>3.480</td>
<td>+14.368</td>
</tr>
<tr>
<td>1970</td>
<td>5.0</td>
<td>675</td>
<td>1200</td>
<td>0.54</td>
<td>0.480</td>
<td>3.980</td>
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<tr>
<td>1971</td>
<td>6.8</td>
<td>700</td>
<td>1300</td>
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<td>0.520</td>
<td>5.720</td>
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<td>1972</td>
<td>8.2</td>
<td>750</td>
<td>1400</td>
<td>0.60</td>
<td>0.560</td>
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<td>1973</td>
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<td>820</td>
<td>1650</td>
<td>0.656</td>
<td>0.660</td>
<td>8.684</td>
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<tr>
<td>1974J</td>
<td>20.0</td>
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<td>1900</td>
<td>1.12</td>
<td>0.760</td>
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<td>1975D</td>
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<td>1900</td>
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<td>1980J</td>
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<td>3800</td>
<td>2.16</td>
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<td>26.12</td>
<td>+1.713</td>
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</table>
TABLE 9.8. Comparative evaluation of shipbuilding cost.
Capital Costs in £ millions (1980).

<table>
<thead>
<tr>
<th>Speed</th>
<th>18 knots</th>
<th>19 knots</th>
<th>21 knots</th>
<th>23 knots</th>
<th>25 knots</th>
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<td>1000 TEU</td>
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</table>

Assumptions: 15% Profit
100% overhead
£215/tonnes steel price shipbuilding average
£2.40/hr wage rate
since early 1976. Fig. 9.10 represents the escalation factors versus the year of construction for various types of ships, and shows that container ship costs have fallen in comparison to the costs of other ship types after 1977. Swift (114) gives two formulae for estimating the cost of the ship when the prices are not fixed but subject to escalation. Also the economic complexities involved in quoting prices in different currencies and subject to fluctuations are also dealt with by Swift (114). In this thesis the container ship costs are assumed to be of fixed contract type at 1980 cost levels in U.K. pounds sterling.
Fig. 9.10. Ship costs, annual escalation.
(By permission of Burness-Corlett & Partners Ltd. (57)).

- Passenger/car ferry
- Container ships
- Dry cargo
- Bulk carriers

0 10 20 30 40 50 60 70

Percent escalation

1960 62 64 66 68 70 72 74 76 78 80

Year ending Dec. 31st
CHAPTER 10

SHIPS OPERATING COSTS

10.0 INTRODUCTION
10.1 MANNING
10.2 CREW COSTS
10.3 INSURANCE
10.4 MAINTENANCE AND REPAIR COSTS
10.5 STORES COSTS
10.6 MISCELLANEOUS COSTS
10.7 PORT CHARGES AND DUES
10.8 FUEL OIL COSTS
10.9 CONTAINER HANDLING COSTS
10.10 OPERATING COSTS
10.0 INTRODUCTION

The estimation of operating costs is one of the most difficult cost items to rationalise. The operating costs vary for ship type, flag of the vessel, age of ship, operating pattern, trade route etc., and even identical ships belonging to the same owner can have different operating costs. The operating costs were built up from equations developed from previous containership studies and validated with some actual operating cost data to reflect 1980 costs. The operating costs therefore reflect average operating cost figures for a U.K. shipowner.

As in developing other cost models such as capital cost and container cost the operating cost model must reflect the correct magnitude of the differences in costs between alternatives as much as the absolute values. The operating costs can be escalated by escalation factors given in Section 10.10 to reflect the costs in a particular year.

Differing accounting procedures and subdivision of the cost elements also makes it difficult to compare costs of two shipping companies. The operating costs are usually subdivided as shown in Fig. 10.1. Containerships are usually operated under the liner conference system where the shipowner may pay all the costs associated with the ship and the profits are pooled together and subdivided amongst the conference member according to their share of the cargo.

To estimate the annual operating costs, it was subdivided into daily running costs which forms a part of the fixed costs, and variable costs which comprises voyage costs and cargo handling costs.

The daily running costs were estimated from
- Crew costs, comprising the crew wages, overtime, leave, study, social security, travel and training.
- Victualling
- Insurance, comprising the hull and machinery, protection and indemnity (P & I) and war risk
**Fig. 10.1.** Breakdown of the total ship costs (115).

<table>
<thead>
<tr>
<th>Economic Classification</th>
<th>Main Categories</th>
<th>COST ITEMS</th>
<th>Allocation of costs in different operations</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Capital Costs</td>
<td>1</td>
<td>Cost of ship (loans etc.)</td>
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<tr>
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<td>2</td>
<td>Interest</td>
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<tr>
<td>Fixed Costs</td>
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<td>3</td>
<td>Profit (return on capital)</td>
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<tr>
<td></td>
<td>Overhead Costs</td>
<td>4</td>
<td>Management (Head Office, Supervision etc.)</td>
</tr>
<tr>
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<td></td>
<td>5</td>
<td>Selling &amp; marketing</td>
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<tr>
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<td>Daily Running Costs</td>
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<td>8</td>
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<td>11</td>
<td>Stores</td>
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<td>Voyage Costs</td>
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<td></td>
<td></td>
<td>18</td>
<td>Cargo Handling</td>
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</table>

- Bareboat Charter
- Time Charter
- Voyage Charter
- Liners

COSTS BORNE BY SHIPOWNER

COSTS BORNE BY CHARTERER

usually:sometimes (liner terms)
- Maintenance and repairs, comprising the hull/outfit and accommodation and hull engineering and machinery.
- Deck and engine stores
- Miscellaneous costs.

The voyage costs were estimated from
- Fuel oil costs, comprising the heavy fuel oil, diesel fuel oil and lub oil costs.
- Port costs, comprising the port entry and exit costs and daily port costs.

To get the annual cost of operating the ship, the container handling costs were added to the operating cost.

A brief description for estimating each of the above costs in pounds sterling and 1980 cost figures are outlined in this chapter. Table 10.1 outlines the operating costs of some ships against which the operating cost model was validated from confidential sources.

10.1. MANNING

One of the principal components of the operating costs is the crew cost and forms about 18% of the total operating cost. The vast difference in crew costs to a shipowner in a particular country is well illustrated in Table 10.2, with American shipowners paying the highest costs. Usually the ships have officers from the developed world and the rest of the crew are from the developing world, who are paid ITF rates or rates negotiated between the seamen's union of a particular country and the shipowners. This is one way of cutting costs, but in many countries there is agreement between the union and government, not to allow seamen from other countries to be employed on ships registered in that country.

The only way to reduce costs in such circumstances is to reduce manning. A typical example is that of Japan ranking 9th w.r.t. to crew costs for a typical bulk carrier/tanker with 32 crew in 1978 (117). A comprehensive experiment
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<th>Total Ins.</th>
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<th>Total Fixed cost AVG</th>
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</table>

**NOTE:** GC = General Cargo, BC = Bulk Carrier, T = Tanker, Cont. = Container, RoRo = Roll on - Roll off, CL = Cargo Liner, D = Diesel, T = Steam Turbine. 1 = Daily costs.
<table>
<thead>
<tr>
<th>Country</th>
<th>Annual Crew Costs to Owner in £</th>
<th>Basic Annual Crew Wages Able Seaman in that Country £</th>
<th>Number of Crew</th>
<th>Factor to convert basic annual crew wages to annual crew costs</th>
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</table>
concerning ship manning systems showed that for a container vessel a crew of 24 could be reduced to 18 by adopting general purpose manning and high degree of automation e.g. 1584 TEU container ship 'Hakuba Maru' (118). Amongst the countries which have been able to reduce their manning successfully are West Germany, Japan, Taiwan, Norway and Sweden (116).

Some typical container ship manning is shown in Table 10.3. An analysis of manning level of 139 container ships was carried out as shown in Fig. 10.2. The ships were categorised into 6 groups according to the flag. Japan, U.S., Far East, Middle East, U.K. and Europe and flag of convenience, and subdivided according to container capacity in Teu into 5 groups, (500-999), (1000-1499), (1500-1999), (2000-2499) and (2500-3000 and above). U.S. manning levels were the highest in all container capacity categories about 40 and Japanese flag ships had the lowest, about 26. Reduced manning was observed in Japanese flag ships about 18 crew for 1576-1588 Teu ship and Liberian flag ship about 16 crew for 1800 Teu ship. U.K. manning was about 30-38 crew and above that of some Far Eastern flag ships.

The range of ship size considered in this thesis is 500 Teu to 2500 Teu, the manning of a U.K. flag ship will be between 34 to 38 crew.

10.2. CREW COSTS

As shown in Fig. 10.3, for a 1288 Teu, 23 knots container-ship the crew costs are about 49% of the daily running costs. Crew costs are easier to calculate though the crew costs for ships under different flags can differ by a factor of 8.

Detailed crew cost estimates were available for 35 general cargo ships and a bulk carrier. Also available were detailed estimates of a shipping company with general purpose manning under British flag and conventional manning under American flag. The methodology is the same once the basic wages (readily available from press and journals) and the
<table>
<thead>
<tr>
<th>No.</th>
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<th>Gross Tonnage</th>
<th>SHP</th>
<th>No. of officers</th>
<th>No. of PO</th>
<th>No. of crew</th>
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<td>29000</td>
<td>15</td>
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<td>Oriental Deck</td>
<td>1278</td>
<td>29000</td>
<td>29000</td>
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</tr>
<tr>
<td>15</td>
<td>New Jersey Maru</td>
<td>1987</td>
<td>37799</td>
<td>69600</td>
<td>31+4</td>
<td>7</td>
<td>31+4</td>
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<tr>
<td>16</td>
<td>Elbe Maru</td>
<td>1842</td>
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<td>84600</td>
<td>32</td>
<td>7</td>
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</tr>
<tr>
<td>17</td>
<td>Selandia</td>
<td>2200</td>
<td>49961</td>
<td>78600</td>
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<td>7</td>
<td>33</td>
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</tr>
<tr>
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<td>Atlantic Marseille</td>
<td>709</td>
<td>13332</td>
<td>18000</td>
<td>10</td>
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<td>27</td>
<td>18000</td>
<td>U.K.</td>
</tr>
<tr>
<td>19</td>
<td>Act 1</td>
<td>1223</td>
<td>24820</td>
<td>30000</td>
<td>16+</td>
<td>2cads.4</td>
<td>16+</td>
<td>24820</td>
<td>U.K.</td>
</tr>
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<td>1556</td>
<td>33400</td>
<td>29000</td>
<td>16</td>
<td>2cads.3</td>
<td>16</td>
<td>33400</td>
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<td>21</td>
<td>Liverpool Bay</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
<td>15</td>
<td>5</td>
<td>16</td>
<td>2500</td>
<td>U.K.</td>
</tr>
<tr>
<td>22</td>
<td>Encounter Bay</td>
<td>1572</td>
<td>1572</td>
<td>1572</td>
<td>15</td>
<td>4</td>
<td>16GP</td>
<td>1572</td>
<td>U.K.</td>
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</tbody>
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228
Fig. 10.2. REPRESENTATIVE MANNING LEVEL

TOTAL NUMBER OF CREW (AVG.)

REF. CONT. INTL. YR. BOOK '81 (139 SHIPS)

<table>
<thead>
<tr>
<th>Flag</th>
<th>JAPAN</th>
<th>U.S.A</th>
<th>FAR EAST</th>
<th>U.K &amp; EUR.</th>
<th>LIB &amp; PAN.</th>
</tr>
</thead>
<tbody>
<tr>
<td>500-999</td>
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<td>1000-1499</td>
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<td>1500-1999</td>
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<td>2000-2499</td>
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<td>2500-3000</td>
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<td>3000-3499</td>
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</tbody>
</table>
Fig. 10.3. **DAILY RUNNING COST OF 1288TEU, 23KNOT**

**ACTUAL DATA FOR CONTAINER SHIP**

- Crew Wages: 43.2%
- Hull Maintenance: 10.5%
- P&I Insurance: 9.8%
- Machinery Maintenance: 9.5%
- Stores Costs: 9.4%
- Hull & M/C Insurance: 7.4%
- Other Crew Costs: 6.2%
- Victualling: 3.8%
- War Risk Insurance: 1.2%
The number of officers, petty officers and ratings are known. The total crew costs were subdivided into:

- Basic wages  ) Basic crew wages
- Overtime
- Study allowance
- Security and insurance  ) Other crew costs
- Travel allowances
- Cost of training
- Leave allowances

Fig. 10.4. shows the contribution of the different elements to the crew costs for an actual container ship.

The costs shown are base rates and can be used for all vessel types with certain additions. Most countries do have minimum rates but owners in many instances exceed these to meet the operational requirements of their trade. The cost figures shown are considered representative.

The following is a brief description of the methodology.

1. The basic wages of each of the officers, petty officers and ratings were collected for ships under British flag from the trade press and shipping companies. For other flags (116, 117) and (118) give representative values. The basic wages of the officers, ratings and petty officers were averaged to simplify the calculation, alternatively the procedure can be repeated for each individual member. The program input therefore requires only the average wages of officers, petty officers and ratings (3 data values) compared to data values of say 36 (for 36 men crew). The basic wages of officers is taken as £8400/annum, petty officers as £5400/annum and ratings as £5300/annum for a 38 man crew comprising of 12 officers, 6 petty officers and 20 ratings.

2. Overtime is available to petty officers and the ratings and was taken as 30% of the basic wages.

3. The leave for officers is taken as 50% of the basic wage and 30% of the basic wage for petty officers and ratings.
Fig. 10.4. **CREW COSTS FOR A 1200 TEU, 23 KNT. SHIP**
ACTUAL VALUES AT 1979 COST LEVEL (Developed World Flag)

- **WAGES: OFFICERS** 56.8%
- **SOC. SECUR. & PENSION** 4%
- **VICTUALLING** 7.7%
- **TRAVELLING** 7.2%
- **WAGES: CREW** 24.3%
(4) Study allowances of up to 6 months is allowed for selected officers, and taken as half the number of officers.
(5) Social security payments of up to 25% of the salary to cover pensions and health insurance (company and government) was assumed.
(6) Travel allowances represents 3 changes/annum for officers and 2 for petty officers and ratings. The cost is based on an average relieving trip.
(7) Training is an estimated cost to cover cadet programmes and in-house facilities.

Table 10.4 outlines the calculation of the above procedure and is adopted in the program. A comparative evaluation for an American owned ship showed that the average basic wages of officers were 1.62 times higher, petty officers 1.17 times higher and ratings 1.37 times higher than a British owned ship for the same manning level, although the former will have higher manning requirements and thus higher costs. This is borne out by Table 10.2 which shows that the American flag ship will have crew costs 1.78 times that of a ship under British flag. Table 10.2 also gives a quick estimating method for derivation of total crew costs for ships under different flags.

10.3. INSURANCE

Insurance consists of Hull and Machinery insurance, protection and indemnity insurance and war risk insurance. There are no precise formulae or methods to calculate insurance costs, and lots of factors are considered e.g. composition of the fleet, previous history, age of the vessels in the fleet, extent of risk an owner is willing to cover etc. Some owners do not cover their ships against all types of risks, when the profits are low. Insurance costs however do not vary as much as crew costs as the shipowner is often free to buy the cheapest in the world market. It is assumed in the thesis that the shipowner is able to buy the cheapest insurance in the world market and he covers most of the risks. Each of the insurances are considered briefly here.
TABLE 10.4. Calculation procedure of crew costs for 38 men crew.

<table>
<thead>
<tr>
<th>Item</th>
<th>Computer Symbol</th>
<th>Calculation</th>
<th>% of Total</th>
<th>Total costs in £</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Wages</td>
<td>CWAGES</td>
<td>[WC_\text{CREW} \times \text{CREW} + W_P \times \text{PO} + W_{OFF} \times \text{OFF} = 5300 \times 20 + 6 \times 5400 + 8400 \times 12 = ]</td>
<td>39.95</td>
<td>239200</td>
</tr>
<tr>
<td>Overtime</td>
<td>COVTIM</td>
<td>[0.30 \times WC_\text{CREW} \times \text{CREW} + 0.30 \times W_P \times \text{PO} = 0.30 \times 5300 \times 20 + 0.30 \times 5400 \times 6 = ]</td>
<td>6.93</td>
<td>41520</td>
</tr>
<tr>
<td>Cost of study</td>
<td>CSTUDY</td>
<td>[0.25 \times \text{OFF} \times W_{OFF} = 0.25 \times 12 \times 8400 = ]</td>
<td>4.21</td>
<td>25200</td>
</tr>
<tr>
<td>Cost of leave</td>
<td>CLEAVE</td>
<td>[0.30 \times WC_\text{CREW} \times \text{CREW} + 0.50 \times W_P \times \text{PO} + 0.50 \times W_{OFF} \times \text{OFF} = 0.30 \times 5300 \times 20 + 0.50 \times 5400 \times 6 + 0.50 \times 8400 \times 12 = ]</td>
<td>16.43</td>
<td>98400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[\text{SALARY} = 0.25 \times \text{SALARY} ]</td>
<td></td>
<td>404320</td>
</tr>
<tr>
<td>Cost of security and insurance</td>
<td>CSECUR</td>
<td>[0.25(\text{CWAGES} + \text{COVTIME} + \text{CSTUDY} + \text{CLEAVE}) = 0.25 \times \text{SALARY} ]</td>
<td>16.88</td>
<td>101080</td>
</tr>
<tr>
<td>Cost of travel, U.K. - Persian Gulf</td>
<td>CTRAVL</td>
<td>[1500 \times \text{OFF} + 1000 \times (\text{CREW} + \text{PO}) = 1500 \times 12 + 1000 \times (20 + 6) = ]</td>
<td>7.35</td>
<td>44000</td>
</tr>
<tr>
<td>Training costs</td>
<td>CTRAIN</td>
<td>[1300.0 \times \text{TMAN} ]</td>
<td>8.25</td>
<td>49400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[\text{TOTAL} = 100.00 ]</td>
<td></td>
<td>598800</td>
</tr>
</tbody>
</table>

WCREW, WPO, WOFF - Wages of ratings, petty officers and officers/annum.
CREW, PO, OFF - Number of ratings, petty officers and officers.
Fig. 10.5 shows the contribution of the different elements of the insurance costs for an actual containership.

**HULL AND MACHINERY INSURANCE**

The hull and machinery insurance covers a shipowner against damage or total loss of the vessel and is mainly dependent on the owner's past safety record. Usually hull and machinery insurance is expressed as a fraction of the price of the ship (54, 119, 120, 46) or Teu (39), (55) or as a function of the machinery acquisition cost (102, 61). (See Table 10.5). The hull and machinery insurance cost in this thesis was expressed as a function of the price of the ship. A check was made with the actual ship data as shown below.

<table>
<thead>
<tr>
<th>Ref. No.</th>
<th>Type</th>
<th>Year</th>
<th>DWT</th>
<th>TEU</th>
<th>Capital Cost in £ x 10^6</th>
<th>Actual HMINS in £</th>
<th>Actual as a % of CAPCOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gen. Cargo</td>
<td>1978</td>
<td>16845</td>
<td>-</td>
<td>3.93</td>
<td>23134</td>
<td>0.588</td>
</tr>
<tr>
<td>2-6</td>
<td></td>
<td>1978</td>
<td>16896</td>
<td>-</td>
<td>3.93</td>
<td>23134</td>
<td>0.588</td>
</tr>
<tr>
<td>7-11</td>
<td></td>
<td>1978</td>
<td>19506</td>
<td>-</td>
<td>7.37</td>
<td>35331</td>
<td>0.479</td>
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<tr>
<td>13</td>
<td></td>
<td>1978</td>
<td>15022</td>
<td>-</td>
<td>5.43</td>
<td>30000</td>
<td>0.552</td>
</tr>
<tr>
<td>14</td>
<td>Bulk Car.</td>
<td>1978</td>
<td>69889</td>
<td>-</td>
<td>20.27</td>
<td>65861</td>
<td>0.325</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>1977</td>
<td>26468</td>
<td>-</td>
<td>7.072</td>
<td>41976</td>
<td>0.593</td>
</tr>
<tr>
<td>17</td>
<td>Container</td>
<td>1980</td>
<td>48544</td>
<td>3000</td>
<td>43.24-48.0</td>
<td>160615-197680</td>
<td>0.371-0.457</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>1979</td>
<td>23016</td>
<td>1288</td>
<td>25.8</td>
<td>67244</td>
<td>0.26</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>1979</td>
<td>28295</td>
<td>1684</td>
<td>30.0</td>
<td>67244</td>
<td>0.24</td>
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</table>

A further check was made with two equations which were developed in 1978, one by Alderton (119) for all ship types and the other by Validakis (120). The formulae are given in Table 10.5.

Actual shipping company records showed that hull and machinery insurance is 0.63% of the value of the ship in the previous year plus 0.283% of the increase in value of the ship for the present year, e.g. for ship 1, the 1978 cost of hull and machinery is calculated as follows.
Fig. 10.5 INSURANCE COSTS FOR 1288TEU, 23KNOT SHIP
ACTUAL VALUES AT 1979 COST LEVEL (European shipowner).

PROTECT & INDEMNITY

56.7%

WAR RISK INSURANCE (0.9%)

42.4%

HULL & MACHINERY INS.
Table 10.5. Summary of operating cost formulae (updated with operating cost indices)

<table>
<thead>
<tr>
<th>Ship Type</th>
<th>Container</th>
<th>Cargo Liner</th>
<th>Container</th>
<th>Container</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Erichsen (39)</td>
<td>Swift (55)</td>
<td>Sen (41)</td>
<td>Volker (61)</td>
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<tr>
<td>Crew Costs</td>
<td>Formula</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wages</td>
<td>( C_0 \times 10^5 \times \text{Teu}^{0.104} \times 1.05^t )</td>
<td>0.43</td>
<td>1.29</td>
<td>0.59</td>
</tr>
<tr>
<td>Victualling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other crew costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance and Repairs</td>
<td>Hull</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hull engineering</td>
<td>( C_1 \times (\text{CNC})^{0.616} \times e^{0.027t} )</td>
<td>165</td>
<td>339</td>
<td>25.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hull outfit &amp; accommodation</td>
<td>( C_2 \times (\text{CN})^{0.685} \times e^{0.0345t} )</td>
<td>211</td>
<td>534</td>
<td>25.46</td>
</tr>
<tr>
<td>Diesel</td>
<td>( C_3 \times \text{BHP} )</td>
<td>1.67</td>
<td>3.27</td>
<td>2.32</td>
</tr>
<tr>
<td>Steam Turbine</td>
<td>( C_4 \times \text{SHP}^{2/3} )</td>
<td>20</td>
<td>41</td>
<td>27.8</td>
</tr>
<tr>
<td>Gas Turbine</td>
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<td></td>
<td></td>
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<tr>
<td>Stores &amp; Supplies</td>
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<tr>
<td>Insurance</td>
<td>Hull &amp; m/c</td>
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<td></td>
</tr>
<tr>
<td>War Risk</td>
<td>( C_5 \times \text{Teu}^{0.7} )</td>
<td>753</td>
<td>907</td>
<td>1042</td>
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<tr>
<td>P &amp; I</td>
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<tr>
<td>Overheads &amp; Miscellaneous</td>
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</table>

Notes: CNC and CN in m³, Costs in £ unless indicated otherwise.
<table>
<thead>
<tr>
<th>Ship Type</th>
<th>Container Hancock (5k)</th>
<th>Container Alderton (119)</th>
<th>All ship types</th>
</tr>
</thead>
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<tr>
<td>Crew Costs</td>
<td>wages + other crew costs</td>
<td>$C_1 \times N_{CREW}$</td>
<td>11,754</td>
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<tr>
<td></td>
<td>Victualling</td>
<td>$C_2 \times N_{CREW}$</td>
<td>313</td>
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<tr>
<td>Number of crew</td>
<td>Engine crew</td>
<td>$=0.1 \times$</td>
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</tr>
<tr>
<td></td>
<td>SHP</td>
<td>1000</td>
<td>+ 8</td>
</tr>
<tr>
<td></td>
<td>Deck crew</td>
<td>$=0.167 \times$</td>
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<tr>
<td></td>
<td></td>
<td>$\frac{CN}{1000}$</td>
<td>+ 5</td>
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<tr>
<td></td>
<td>Total</td>
<td>$= 1.25 \times$</td>
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<td></td>
<td></td>
<td>${ENG + DECK}$</td>
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<tr>
<td>Hull</td>
<td>Hull outfit 2)</td>
<td>$= \frac{CN}{1000}$</td>
<td>0.67</td>
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</tr>
<tr>
<td></td>
<td>Chapman (146)</td>
<td>Validakis (120)</td>
<td></td>
</tr>
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</tr>
<tr>
<td></td>
<td>1969</td>
<td>1980</td>
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</tr>
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<td>Crew Costs</td>
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</tr>
<tr>
<td>Wages</td>
<td>$C_1 \times NCREW$</td>
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</tr>
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<td>Other crew costs</td>
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</tr>
<tr>
<td>Victualling</td>
<td>$C_2 \times NCREW$</td>
<td>175</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>352</td>
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</tr>
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<td>Maintenance and Repair</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Hull</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hull outfit and accommoda-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>tion 1) Salvage</td>
<td></td>
<td>1629</td>
<td></td>
</tr>
<tr>
<td>Association</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hull engineering</td>
<td>$C_3 \times \left(\frac{CN}{100}\right)^{2/3}$</td>
<td>269</td>
<td></td>
</tr>
<tr>
<td>2) Norwegian Shipowners'</td>
<td>$C_1 + C_2 \times DWT\text{tonnes}$</td>
<td>552</td>
<td></td>
</tr>
<tr>
<td>Association</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam Turbine</td>
<td>$C_4 \times (\text{SHP})^{2/3}$</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Turbine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stores and Supplies</td>
<td>$C_5 \times (\text{NCREW})^{10}$</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td></td>
<td>46</td>
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<td></td>
</tr>
<tr>
<td>Insurance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hull &amp; m/c.</td>
<td>$C_6 + 0.0075 \times \text{PRICE}$</td>
<td>1430</td>
<td></td>
</tr>
<tr>
<td>War Risk</td>
<td>$0.0075 \times \text{CAPITAL CHARGE}$</td>
<td>0.005 \times \text{PRICE}</td>
<td></td>
</tr>
<tr>
<td>P &amp; I</td>
<td>$0.0175 \times \text{GRT}$</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Overheads and</td>
<td>$C_7 + C_8 \left(\frac{CN}{100}\right)$</td>
<td>12,800</td>
<td></td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>$C_7 \times C_8$</td>
<td>43,448</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_7 \times C_8$</td>
<td>141</td>
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<tr>
<td></td>
<td>$C_7 \times C_8$</td>
<td>479</td>
<td></td>
</tr>
</tbody>
</table>
The value of the ship in previous year (1976) \( 3.145 \times 10^6 @ 0.63\% = £19818 \)

Increased value (1977) \( 786432 @ 0.283\% = \frac{£22229}{£22047} \)

Add 10% increase for 1978 \( = £1087 \)

£23134

<table>
<thead>
<tr>
<th>Ref. No.</th>
<th>Alderton '78 £</th>
<th>Validakis (2) in £</th>
<th>(1)/(2) actual</th>
<th>(2) actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>fn(DWT)</td>
<td>fn(PRICE) Total</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>25268 31890 57158</td>
<td>53150</td>
<td>1.075</td>
<td>2.221</td>
</tr>
<tr>
<td>2-6</td>
<td>25344 31890 57234</td>
<td>53150</td>
<td>1.076</td>
<td>2.224</td>
</tr>
<tr>
<td>7-11</td>
<td>28799 33900 62698</td>
<td>56500</td>
<td>1.109</td>
<td>1.488</td>
</tr>
<tr>
<td>13</td>
<td>22533 16250 38823</td>
<td>27150</td>
<td>1.429</td>
<td>1.294</td>
</tr>
<tr>
<td>14</td>
<td>104834 60810 65643</td>
<td>101350</td>
<td>1.634</td>
<td>2.515</td>
</tr>
<tr>
<td>15</td>
<td>39000 21216 60216</td>
<td>35360</td>
<td>1.703</td>
<td>1.435</td>
</tr>
<tr>
<td>17</td>
<td>72816 129720 202536</td>
<td>216200</td>
<td>0.937</td>
<td>1.261</td>
</tr>
<tr>
<td>20</td>
<td>34892 77400 112292</td>
<td>129000</td>
<td>0.870</td>
<td>1.669</td>
</tr>
<tr>
<td>21</td>
<td>34604 90000 124604</td>
<td>150000</td>
<td>0.830</td>
<td>1.853</td>
</tr>
</tbody>
</table>

While Alderton's and Validakis' figures are comparatively equal, they are twice the actual figures. The following equation was adopted in the thesis

\[
\text{Hull and machinery insurance} = \frac{0.40}{100} \times \text{CAPITAL COST OF SHIP} \quad £
\]

Eq. (10.1)

**PROTECTION AND INDEMNITY INSURANCE**

Protection and indemnity (P & I) insurance protects the shipowner against special liabilities. The P & I insurance varies considerably from ship to ship and depends on the size of the ship (GRT), shipowner's loss record, whether or not cargo is included, amount deductible and size of the ship's complement (102, 54). Past container studies have expressed P & I as a function of building cost of the ship (61) or GRT (120, 119) or number of crew (54, 51) or capital
charge (46), Table 10.5. P & I rates are usually quoted in terms of GRT (51) so the P & I insurance was made a function of GRT. A check was made with actual ship data and with the method given by Alderton (119) and Validakis (120).

<table>
<thead>
<tr>
<th>Ref. No.</th>
<th>Actual P &amp; I Insurance</th>
<th>GRT</th>
<th>P &amp; I GRT</th>
<th>Validakis GRT Year = 78</th>
<th>Alderton GRT Year = as given</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55734</td>
<td>12057</td>
<td>4.623</td>
<td>1.1</td>
<td>1.825</td>
</tr>
<tr>
<td>2-6</td>
<td>55539</td>
<td>12015</td>
<td>4.622</td>
<td>1.1</td>
<td>1.825</td>
</tr>
<tr>
<td>7-11</td>
<td>60092</td>
<td>14434</td>
<td>4.163</td>
<td>1.1</td>
<td>1.825</td>
</tr>
<tr>
<td>13</td>
<td>10000</td>
<td>9112</td>
<td>1.097</td>
<td>1.1</td>
<td>1.825</td>
</tr>
<tr>
<td>14</td>
<td>20938</td>
<td>40689</td>
<td>0.515</td>
<td>1.1</td>
<td>1.850</td>
</tr>
<tr>
<td>17</td>
<td>24710</td>
<td>58889</td>
<td>0.419</td>
<td>1.1</td>
<td>1.850</td>
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<tr>
<td>20</td>
<td>89935</td>
<td>25993</td>
<td>3.46</td>
<td>1.1</td>
<td>1.850</td>
</tr>
<tr>
<td>21</td>
<td>89935</td>
<td>24433</td>
<td>3.46</td>
<td>1.1</td>
<td>1.850</td>
</tr>
</tbody>
</table>

whereas Validakis gives a low value of £1.1/GRT, Alderton's figure of £1.850/GRT seems reasonable. Actual 1978 costs of a general cargo ship was calculated on the basis of £2.8/GRT to which was added further premiums to arrive at a figure of £4.6/GRT for a shipowner from the developing world. For an average shipowner with satisfactory past record protection and indemnity insurance (P & I) is given by

\[ P & I \text{ Insurance} = 2.0 \times GRT \]  

Eq. (10.2)

**WAR RISK INSURANCE**

This insurance covers a shipowner against damage in case of hostilities and would cover a shipowner until the vessel reached a port of refuge where a government war-risk scheme could be introduced (121). Benford (51) expresses war risk insurance as 0.1% of the capital cost whereas Hancock (54) takes a higher percentage of 0.2% of the capital cost, Table 10.5. A check for the actual percentage is made for some actual ship data.
These values show that the war risk insurances are less than what is given by Benford or Hancock. A shipping company's actual records showed that it is calculated on the basis 0.063% of the value of the ship. In this thesis a value of 0.01% of the capital cost is taken as a representative figure.

War risk insurance = \( \frac{0.01}{100} \times \text{CAPITAL COST} \) £ Eq. (10.3)

TOTAL INSURANCE

Instead of calculating each of the insurance costs, the total insurance cost can be expressed as a function of Teu (39, 55) or the capital cost (101, 41). Buxton gives a figure of 1.3% of the capital cost (101). A check made against actual data shows that the total insurance costs varied between 1.5% to 2% of the price of the ship, as shown in Table 10.6.

Table 10.7 gives the total insurance costs calculated by the program which are about 0.6% of the capital costs, and shows that there are large variations between the actual data and those calculated by the program.

The program calculates the war risk and hull and machinery insurance as a percentage of the capital cost of the ship. The capital cost of a container ship is about 20 to 40% higher than the price (see Fig. 9.9, 1978), therefore the
TABLE 10.6. Insurance costs as a percentage of the price of the ship.

<table>
<thead>
<tr>
<th>Ref. No.</th>
<th>Ship Type</th>
<th>Actual Total Insurance £</th>
<th>Price of the ship £ x 10^6</th>
<th>Percentage of Capital Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>G.C.</td>
<td>81467</td>
<td>3.93</td>
<td>2.07</td>
</tr>
<tr>
<td>2-6</td>
<td>G.C.</td>
<td>81272</td>
<td>3.93</td>
<td>2.067</td>
</tr>
<tr>
<td>7-11</td>
<td>G.C.</td>
<td>102243</td>
<td>7.37</td>
<td>1.387</td>
</tr>
<tr>
<td>24</td>
<td>Cont.</td>
<td>206438</td>
<td>13.76</td>
<td>1.50</td>
</tr>
<tr>
<td>25</td>
<td>Cont.</td>
<td>88474</td>
<td>5.90</td>
<td>1.499</td>
</tr>
<tr>
<td>26</td>
<td>Ro-Ro</td>
<td>147456</td>
<td>9.83</td>
<td>1.50</td>
</tr>
<tr>
<td>27</td>
<td>Ro-Ro</td>
<td>52160</td>
<td>6.14</td>
<td>1.50</td>
</tr>
<tr>
<td>28</td>
<td>Car. liner</td>
<td>129024</td>
<td>8.60</td>
<td>1.50</td>
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</table>
### TABLE 10.7. Insurance costs, actual versus calculated.

<table>
<thead>
<tr>
<th>Ref. No.</th>
<th>Vessel Type</th>
<th>Actual Total Insurance £</th>
<th>PROGRAM VALUES (1978)</th>
<th>Total</th>
<th>Percentage of Capital Cost</th>
<th>% Diff. from actual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>P &amp; I</td>
<td>War</td>
<td>Hull + M/C</td>
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</tr>
<tr>
<td>14</td>
<td>Bulk. Car.</td>
<td>99875</td>
<td>74257</td>
<td>2027</td>
<td>81080</td>
<td>157364</td>
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<tr>
<td>1</td>
<td>Gen. Car.</td>
<td>81467</td>
<td>22004</td>
<td>1063</td>
<td>42520</td>
<td>65587</td>
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<tr>
<td>2-6</td>
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<td>81272</td>
<td>21927</td>
<td>1063</td>
<td>42520</td>
<td>65510</td>
</tr>
<tr>
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<td>Gen. Car.</td>
<td>102243</td>
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<td>1130</td>
<td>45200</td>
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<tr>
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<td>Gen. Car.</td>
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</tr>
<tr>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>27</td>
<td>Ro-Ro</td>
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<td>9077</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>28</td>
<td>Car. liner</td>
<td>129024</td>
<td>18354</td>
<td>-</td>
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total insurance costs as 0.6% of the capital costs seems reasonable.

10.4. MAINTENANCE AND REPAIR COSTS

Maintenance and repair costs usually consist of the cost related to dry docking of the ship, maintenance of engines, the main systems, cost associated with other preventive maintenance, repair to damages, cost of inventory related to spares and equipment and tools.

The maintenance and repair costs were subdivided into hull and outfit maintenance and machinery maintenance. Machinery maintenance is usually subdivided according to the type of engine e.g. diesel, steam turbine or gas turbine. In the program only diesel engine maintenance and repair costs are estimated. Figure 10.6 shows the percentage contribution of elements of the maintenance and repair costs for an actual container ship. In the program, however, luboil costs are calculated separately.

HULL AND OUTFIT MAINTENANCE AND REPAIRS

The hull and outfit maintenance costs comprises mainly of drydocking costs of the ship as shown in Fig. 10.6. Past container ship studies have expressed the hull and outfit maintenance cost as a function of the cubic number (54), (46), (55), (41), (39). A similar approach has been taken in the thesis. Formula developed for general cargo ships by Benford (51) and subsequently incorporated for a container ship study by Hancock (54) & Chapman (46) was updated to 1980 cost levels. Two indices were available for updating the cost figures. One published by the Salvage Association is based on world wide figures and cost indices, for major ship repairing facilities are given together with the cost of hull and machinery repair for a typical ship at different ship repairing facilities (122). The other was the operating cost indices published annually by the Norwegian Shipowners Association (123). The indices given by the latter was
Repairs & Maintenance Cost for 1288 TEU, 23kt Ship

Actual Values at 1979 Cost Level (European shipowner).
adopted because the indices for various other operating costs were also available, and were used for updating other cost items. The hull and outfit maintenance (CHMANT) cost is given by

\[ CHMANT = 450 \times (CN)^{0.67} \text{ £ (1980) Eq. (10.4a)} \]

\[ = 440 \times (CN)^{0.67} \text{ £ (1978) Eq. (10.4b)} \]

MACHINERY MAINTENANCE AND REPAIR

Machinery maintenance and repair forms a substantial part of the total maintenance and repair cost particularly for diesel machinery plant. Steam turbine plants have substantially lesser maintenance and repair costs, Table 10.1. But due to increases in fuel costs, the diesel plant with its lower fuel consumption is preferred.

The machinery maintenance and repair costs for container ships with diesel plant is usually expressed as a function of BHP (39), (55) and (41). A similar expression was adopted in the thesis, and Erichsen's (39), Swift (55), Sen (41) figures were updated by indices given by the Norwegian Shipowner's Association (123).

The machinery maintenance and repair cost (CMMANT) is given by

\[ CMMANT = 3.27 \times \text{BHP} \text{ £ (1980) Eq. (10.5a)} \]

\[ = 2.57 \times \text{BHP} \text{ £ (1978) Eq. (10.5b)} \]

The machinery maintenance costs are of the right magnitude, e.g. 1976 costs for diesel plant was £2.47 to £3.46/bhp/annum (124) with £2.72/bhp/annum as the average cost and 1980 costs were £2.5/bhp/annum (66).

TOTAL MAINTENANCE AND REPAIR COSTS

The total maintenance costs are difficult to correlate to actual data. The percentage variation of total ship maintenance and repair costs as given by the Salvage Association (122), with U.K. costs as 100, showed that world wide repair and maintenance costs can vary between 57 to
225. It is difficult to validate the equations for hull and outfit and machinery separately. Since machinery maintenance is of the correct magnitude, a check on the total maintenance and repair costs with total costs of actual ships (Table 10.1) would show if the hull/outfit maintenance and repair costs are of the correct magnitude.

Actual maintenance and repair costs were twice the calculated values as shown in Table 10.8.

A further check was made with two other equations which were available for 1978, one by Validakis (120) for general cargo ships and the other by Alderton (119) for all ship types. These methods also gave values which were of the same magnitude, Table 10.9, as those calculated by Eq. (10.4a and 10.5a). So these equations were adopted in the program to represent maintenance and repair costs.

10.5. STORE COSTS

Store costs include the cost of deck and engine stores and the cabin stores. Included in the deck and engine stores are paints (excluding paint cost in dry dock), ropes, packing and engine spares etc. and cabin stores includes all supplies, soft furnishings, laundry etc. Store costs are usually a function of the number of crew (46), (120), (54), (51). Three forms of equations were used in the past studies as shown in Table 10.5 and are:

Stores and supplies cost = \( C_0 \left( \frac{\text{NCREW}}{10} \right)^4 \), Benford (51) and Chapman (46)

or Stores and supplies cost = \( C_0 + C_1 \times \text{NCREW} \), Validakis (120)

or Stores and supplies cost = \( C_0 \times \text{NCREW} \), Hancock (54)

Since store costs form only 9.4% of the daily running costs (Fig. 10.3) Hancock's linear relationship was adopted and coefficient \( C_0 \) determined from actual ship data (Table 10.1).
## TABLE 10.8. Maintenance and repair costs, actual versus calculated.

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* For steam turbine the machinery maintenance and repair costs for 1978 were taken as

\[ CMMANT = 6550(CN)^{0.67} \]

CN in m³
TABLE 10.9. Comparative evaluation of maintenance and repair costs.

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TABLE 10.10. Actual stores and supplies costs vs. estimated.

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A linear regression on the above data gave the following equation

Stores and supplies costs = 41279 - 20.95 x NCREW

with a correlation of (-0.0033) showing an extremely poor fit to the data. Validakis (120) stores and supplies includes luboil costs, once the actual luboil costs are subtracted gives reasonable values for general cargo vessels but gives poor results for container ships (Table 10.10). Store costs were updated from Hancock (54) by operating cost indices (123) and was adopted in the program. Table 10.10 shows

*Estimated number of crew.
the calculated values at 1978 cost levels which seem reasonable. For 1980 cost levels the store costs are given by

\[
\text{Stores costs} = 1666 \times N\text{CREW} \quad \text{\pounds} \quad \text{Eq. (10.6)}
\]

10.6. MISCELLANEOUS COSTS

Miscellaneous costs include the cost to cover crew recruitment, communications, standby, medical and short backup directly linked with crewing, sundries and administration.

This cost is either taken as a fixed cost (119) or is made a function of cubic number of the ship (46), (51) (see Table 10.5). Following equations were available.

METHOD 1: The following equation was used for a container ship study by Chapman (46), and was updated from an equation suggested by Benford (51) for a general cargo ship. The equation was updated by operating cost indices given by Norwegian Shipowner's Association (123).

\[
\begin{align*}
\text{CADMIN1} &= 12800 + 141\left(\frac{CN}{1000}\right) \quad \text{\pounds} \quad (1969 \text{ cost level}), \text{ CN in m}^3 \\
&= 32906 + 363 \left(\frac{CN}{1000}\right) \quad \text{\pounds} \quad (1978 \text{ cost level}) \\
&= 36419 + 402 \left(\frac{CN}{1000}\right) \quad \text{\pounds} \quad (1979 \text{ cost level}) \\
&= 43444 + 479 \left(\frac{CN}{1000}\right) \quad \text{\pounds} \quad (1980 \text{ cost level})
\end{align*}
\]

METHOD 2: The following equation was suggested by Alderton (119) for all ship types and was updated by operating cost indices (123).

\[
\begin{align*}
\text{CADMIN2} &= 7942 \quad \text{\pounds} \quad (1969 \text{ cost level}) \\
&= 31390 \quad \text{\pounds} \quad (1978 \text{ cost level}) \\
&= 34310 \quad \text{\pounds} \quad (1979 \text{ cost level}) \\
&= 40880 \quad \text{\pounds} \quad (1980 \text{ cost level})
\end{align*}
\]

These equations were compared with some actual data (see Table 10.1).

\# indicates updated equation.
Method 1 and Method 2 gave comparable results as shown above, although for Ship No. 21 and 22, the calculated costs were twice the actual figure. Actual cost estimates of 2 shipping companies showed that the miscellaneous cost or cost of administration is apportioned for each vessel in the fleet according to the number of crew. Since this relationship gives acceptable results, it was used in the program and is given by

\[ CMISC = 1300.0 \times NCREW \]  
\[ £ \ (1980 \text{ cost level}) \] Eq. (10.7)

10.7. PORT CHARGES AND DUES

A ship incurs two types of costs when calling at a port. One cost is associated with entering and exiting the port, such as pilotage, towage, canal dues etc. The second is related to the time a ship stays in the port which consists of daily charges for berthing privileges, watchman fees, utility hook ups for water and electricity at the pier etc.

Port costs (Table 10.11) are usually made a function of the net registered tonnage (119), (107), cargo dead weight (41) or bale cubic (125) per port of call, or as a fixed cost per round trip (40). Container ship study by Swift (55) subdivided the port costs into those incurred per day and the others which are incurred per call for
<table>
<thead>
<tr>
<th>Method</th>
<th>Cost level</th>
<th>Formulae</th>
<th>Constants</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1978</td>
<td>TCPORT = $C_1 \times \text{GRT} + C_2 \times \text{GRT x DIP in £/call}$</td>
<td>$C_1$</td>
<td>0.512</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C_2$</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>2 1978</td>
<td>TCPORT = $C_3 \times \text{DWT} + C_4 \times \text{DWT x DIP in £/call}$</td>
<td>$C_3$</td>
<td>0.306</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C_4$</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>3 1978</td>
<td>TCPORT = $C_5 \times \text{NRT in £/call}$</td>
<td>$C_5$</td>
<td>3.32 to 2.40</td>
<td>119</td>
</tr>
<tr>
<td></td>
<td>TCPORT = $C_6 \times \text{NRT in £/call}$</td>
<td>$C_6$</td>
<td>2.50</td>
<td></td>
</tr>
<tr>
<td>4 1978</td>
<td>TCPORT = $C_7 \times \text{NRT in £/call}$</td>
<td>$C_7$</td>
<td>0.3 to 3.0</td>
<td>107</td>
</tr>
<tr>
<td>5 1973</td>
<td>TCPORT = $C_8 \times \text{Cargo deadwt. in £/call}$</td>
<td>$C_8$</td>
<td>0.147</td>
<td>41</td>
</tr>
<tr>
<td>6 1968</td>
<td>TCPORT = $C_9 \times \text{bale cubic capacity (m}^3\text{) in £/call}$</td>
<td>$C_9$</td>
<td>14.75</td>
<td>125</td>
</tr>
<tr>
<td>7 1973</td>
<td>Cost/call = $C_{10} + C_{11} \times \frac{\text{CN(m}^3\text{)}}{1000}$ in £</td>
<td>$C_{10}$</td>
<td>222</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C_{11}$</td>
<td>638</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cost/day in port = $C_{12} + C_{13} \times \frac{\text{CN(m}^3\text{)}}{1000}$ in £</td>
<td>$C_{12}$</td>
<td>18.94</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C_{13}$</td>
<td>274</td>
<td></td>
</tr>
<tr>
<td>8 1974</td>
<td>Cost/round trip = $C_{14}$</td>
<td>$C_{14}$</td>
<td></td>
<td>40</td>
</tr>
</tbody>
</table>
every port of call.

There is however wide variation in port costs. Buxton (107) gives a variation between £0.3 to £3.0 per net registered tonnage per port of call, a factor of ten. Because of these wide variations, in the program the method developed by Frankel (53) 1973 was adopted to reflect world wide port costs. This method was updated and subsequently used by Hancock (54) 1972 in a container ship study. The method is described briefly here, and validated with actual port costs of two container ships and with disbursement accounts of ships published by BIMCO (126).

**Entry and exit costs:**

The port entry and exit costs/port of call is given by

\[ P_i = K_i e^{L} \cdot GRT^{0.585} \quad i = 1, 2, 3, 4, 5 \quad £/call \quad \text{Eq. (10.8)} \]

where \( L = \) labour ratio in the trade area, \( 0 < L \leq 1 \)

\( K_i \) = port entry and exit costs constant (see Table 10.12 Col. 2)

**Daily costs:**

The cost in port/day is given by the following equation

\[ P_j = 34 + K_j L^{0.5} \cdot GRT^{0.67} \quad j = 1, 2, 3, 4, 5 \quad £/day \quad \text{Eq. (10.9)} \]

where \( K_j \) = Port daily cost constant (see Table 10.12 Col. 3)

\( GRT = \) Gross registered tonnage in tons.

The \( K_i \) and \( K_j \) terms shown above in each of the equations were given five values. These correspond to three values, high, low and average and two values between high-average and low-average.

Frankel while arriving at these equations got a correlation of about 0.90, but the magnitude of variation was extremely large (53) which was primarily due to institutional, geographical and political factors surrounding each port and the different methods used by various ports.
### TABLE 10.12. Port cost constants.

<table>
<thead>
<tr>
<th>Foreign countries in the trade area</th>
<th>I/J</th>
<th>Labour Ratio</th>
<th>Const. entry &amp; exit cost</th>
<th>Const. daily cost</th>
<th>Port examined in the trade area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenland, Iceland, Ireland, England, Scotland</td>
<td>1</td>
<td>0.42</td>
<td>11.6</td>
<td>2.7</td>
<td>London, Dublin</td>
</tr>
<tr>
<td>Denmark, Norway, Sweden, Finland</td>
<td>2</td>
<td>0.92</td>
<td>3.6</td>
<td>2.10</td>
<td>Gothenberg, Oslo</td>
</tr>
<tr>
<td>W. Germany, France, Holland</td>
<td>3</td>
<td>0.89</td>
<td>7.6</td>
<td>2.7</td>
<td>Bremen, Le Havre, Rotterdam</td>
</tr>
<tr>
<td>Portugal, Spain, Italy, Switzerland, Austria, Yugoslavia, Greece, Albania</td>
<td>4</td>
<td>0.33</td>
<td>11.6</td>
<td>1.50</td>
<td>Genoa, Bilbao</td>
</tr>
<tr>
<td>U.S.S.R., Poland, Bulgaria, Hungary, Czechoslovakia, E. Germany</td>
<td>5</td>
<td>0.39</td>
<td>11.6</td>
<td>3.3</td>
<td>Gdynia, Wismar</td>
</tr>
<tr>
<td>Turkey, Lebanon, Syria, Iraq, Iran, Israel, S. Arabia &amp; Peninsula</td>
<td>6</td>
<td>0.26</td>
<td>5.6</td>
<td>0.70</td>
<td>Kurramshahr, Beirut</td>
</tr>
<tr>
<td>Africa West Coast &amp; Central Africa</td>
<td>7</td>
<td>0.029</td>
<td>7.6</td>
<td>0.70</td>
<td>Lagos, Matadi, Monrovia</td>
</tr>
<tr>
<td>Morocco, Algeria, Tunisia, Libya, UAR</td>
<td>8</td>
<td>0.27</td>
<td>7.6</td>
<td>0.70</td>
<td>Tripoli, Casablanca</td>
</tr>
<tr>
<td>Angola, S. Africa, Mozambique, Zimbabwe</td>
<td>9</td>
<td>0.27</td>
<td>9.6</td>
<td>2.10</td>
<td>Capetown, Beira</td>
</tr>
<tr>
<td>Sudan, Ethiopia, Repub. of Kenya, Tanzania, Uganda, Rwanda, Malawi, Zambia</td>
<td>10</td>
<td>0.029</td>
<td>11.6</td>
<td>0.70</td>
<td>Djibouti, Mombasa</td>
</tr>
<tr>
<td>Afghanistan, Pakistan, India, Nepal, Ceylon</td>
<td>11</td>
<td>0.018</td>
<td>7.6</td>
<td>3.3</td>
<td>Calcutta, Karachi</td>
</tr>
<tr>
<td>Burma, Thailand, Malaysia, Cambodia, S. Vietnam, Philippines, Indonesia</td>
<td>12</td>
<td>0.039</td>
<td>5.6</td>
<td>2.1</td>
<td>Tandjong, Priok, Manila</td>
</tr>
<tr>
<td>Australia, New Zealand</td>
<td>13</td>
<td>0.68</td>
<td>7.6</td>
<td>3.3</td>
<td>Auckland, Sydney</td>
</tr>
<tr>
<td>Japan, Ryukyu, S. Korea, Taiwan</td>
<td>14</td>
<td>0.39</td>
<td>5.6</td>
<td>0.70</td>
<td>Keelung, Yokohama</td>
</tr>
<tr>
<td>China, N. Korea, Vietnam, Hong Kong, Singapore</td>
<td>15</td>
<td>0.05</td>
<td>5.6</td>
<td>1.5</td>
<td>Hong Kong, Singapore</td>
</tr>
<tr>
<td>Foreign countries in the trade area</td>
<td>I/J</td>
<td>Labour Ratio</td>
<td>Const. entry &amp; exit cost</td>
<td>Const. daily cost</td>
<td>Port examined in the trade area</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>-----</td>
<td>--------------</td>
<td>--------------------------</td>
<td>-------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Guatemala, Honduras, Costa Rica, Panama, Nicaragua, San Salvador</td>
<td>16</td>
<td>0.09</td>
<td>11.6</td>
<td>2.1</td>
<td>Balboa, Kingston</td>
</tr>
<tr>
<td>Antilles, Colombia, Venezuela, Surinam, Caracao, Guyana</td>
<td>17</td>
<td>0.17</td>
<td>9.6</td>
<td>2.1</td>
<td>La Guarira, Cartagena</td>
</tr>
<tr>
<td>Brazil, Uruguay, Paraguay</td>
<td>18</td>
<td>0.14</td>
<td>9.6</td>
<td>3.3</td>
<td>Rio de Janeiro, Montevideo</td>
</tr>
<tr>
<td>Ecuador, Peru, Bolivia, Chile</td>
<td>19</td>
<td>0.095</td>
<td>11.6</td>
<td>1.5</td>
<td>Callao, Valparaiso</td>
</tr>
<tr>
<td>U.K. Coastal Area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East Coast</td>
<td>20</td>
<td>0.51</td>
<td>11.6</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>West Coast</td>
<td>21</td>
<td>0.51</td>
<td>11.6</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>United States</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East Coast</td>
<td>22</td>
<td>1.00</td>
<td>11.6</td>
<td>2.1</td>
<td>Baltimore, Boston, New York</td>
</tr>
<tr>
<td>Gulf Coast</td>
<td>1.00</td>
<td>11.6</td>
<td>2.1</td>
<td></td>
<td>Houston, Mobile, New Orleans</td>
</tr>
<tr>
<td>Pacific Coast</td>
<td>1.00</td>
<td>5.6</td>
<td>1.5</td>
<td></td>
<td>Los Angeles, Longview, San</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Francisco, Seattle</td>
</tr>
</tbody>
</table>

* 1. See note 1 for updating these factors.
Heggie (127) based on port dues published in (128) has compared various port costs for four general cargo vessels in nine ports found that the structure of dues varies substantially between the nine ports. Amongst the various factors, there were also subsidies for national flag ships and reduced tariff for liner services etc. Such factors are neglected in constructing this model and the basis of costing is rationalised by assuming that all costs are dependent on the gross registered tonnage of the ship.

The labour ratio col. 1 Table 10.12 was updated by dividing the average per capita income of each trade area by the per capita income of the U.S.A. and is shown in Table 10.13. Table 10.12, col. 2, the entry and exit cost constants and col. 3, the daily cost constants were updated by material and labour indices given in Table 10.14 (see note 1).

The program uses as input the following values: -
PORTD and PORTF, the number of domestic and foreign ports;
PCFD and PCFF, the daily port costs constants;
PECFD and PECFF, the port entry and exit cost constants;
RLABD and RLABF, the labour ratio; at domestic and foreign ports respectively.

The daily port costs are calculated by Eq. (10.9) for the domestic ports and the foreign ports. The average of the daily costs of domestic and the foreign ports is the total daily port costs. The total entry and exit costs is the sum of the entry and exit costs at domestic ports and foreign ports calculated by Eq. (10.8).

Daily costs at the domestic ports, $PCOSTD = DIP \times (34.0 + PCFD \times RLABD^{0.5} \times GRT^{0.67}) \ £$

Daily costs at the foreign ports, $PCOSTF = DIP \times (34.0 + PCFF \times RLABF^{0.5} \times GRT^{0.67}) \ £$

Annual daily port costs, $PDCOST = \frac{(PCOSTD + PCOSTF) \times RTPA}{2}$

where $RTPA = \text{no. of round trips per annum}$. 

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TABLE 10.13. Labour ratio.

<table>
<thead>
<tr>
<th>Area</th>
<th>Average (1) per capita income US$</th>
<th>Labour ratio US = 1.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3655</td>
<td>0.42</td>
</tr>
<tr>
<td>2</td>
<td>7997</td>
<td>0.92</td>
</tr>
<tr>
<td>3</td>
<td>7725</td>
<td>0.89</td>
</tr>
<tr>
<td>4</td>
<td>2830</td>
<td>0.33</td>
</tr>
<tr>
<td>5</td>
<td>3391</td>
<td>0.39</td>
</tr>
<tr>
<td>6</td>
<td>2270</td>
<td>0.26</td>
</tr>
<tr>
<td>7</td>
<td>250</td>
<td>0.029</td>
</tr>
<tr>
<td>8</td>
<td>2305</td>
<td>0.27</td>
</tr>
<tr>
<td>9</td>
<td>2320</td>
<td>0.27</td>
</tr>
<tr>
<td>10</td>
<td>247</td>
<td>0.029</td>
</tr>
<tr>
<td>11</td>
<td>160</td>
<td>0.018</td>
</tr>
<tr>
<td>12</td>
<td>333</td>
<td>0.039</td>
</tr>
<tr>
<td>13</td>
<td>5855</td>
<td>0.68</td>
</tr>
<tr>
<td>14</td>
<td>3410</td>
<td>0.39</td>
</tr>
<tr>
<td>15</td>
<td>463</td>
<td>0.05</td>
</tr>
<tr>
<td>16</td>
<td>850</td>
<td>0.09</td>
</tr>
<tr>
<td>17</td>
<td>1464</td>
<td>0.17</td>
</tr>
<tr>
<td>18</td>
<td>1200</td>
<td>0.14</td>
</tr>
<tr>
<td>19</td>
<td>828</td>
<td>0.095</td>
</tr>
<tr>
<td>20</td>
<td>4430</td>
<td>0.51</td>
</tr>
<tr>
<td>21</td>
<td>4430</td>
<td>0.51</td>
</tr>
<tr>
<td>22</td>
<td>8640</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Note: 1.

Ref. Frankel & Marcus (53) Table exhibit I-11 was updated in the following way.

Daily Costs

\[17 \times \text{Material Index} \times \text{Exchange Rate} (1967-70)(1970-79)1979\]

\[17 \times 1.048 \times 3.885 \times 0.4915 = 34.0\]

Port Constant Col. 3

Daily Costs

Col. 3 exhibit 1-11 x Matl. Index x Matl. Index (67-70) (70-79) *Exchange rate

\[= \text{Col. 3} \times 1.048 \times 3.885 \times 0.4915 = 2.0\]

Port Constant Col. 2

Entry & Exit Costs

Col. 2 exhibit I-11 x Matl. Index (67-70) x Matl. Index (70-79) x Exchange Rate

\[= \text{Col}.2 \times 1.048 \times 3.885 \times 0.4915 = 2.0\]

<table>
<thead>
<tr>
<th>Year</th>
<th>Material Indices</th>
<th>Labour Indices</th>
<th>Av. Weekly Pay £/Wk.</th>
</tr>
</thead>
<tbody>
<tr>
<td>68</td>
<td>97.04</td>
<td>76.77</td>
<td>29.16</td>
</tr>
<tr>
<td>69</td>
<td>98.47</td>
<td>82.78</td>
<td>31.44</td>
</tr>
<tr>
<td>70</td>
<td>100.00</td>
<td>100.00</td>
<td>37.98</td>
</tr>
<tr>
<td>71</td>
<td>113.00</td>
<td>94.63</td>
<td>35.94</td>
</tr>
<tr>
<td>72</td>
<td>117.40</td>
<td>106.21</td>
<td>40.34</td>
</tr>
<tr>
<td>73</td>
<td>129.10</td>
<td>139.42</td>
<td>52.95</td>
</tr>
<tr>
<td>74</td>
<td>183.20</td>
<td>160.32</td>
<td>60.89</td>
</tr>
<tr>
<td>75</td>
<td>245.90</td>
<td>188.05</td>
<td>71.42</td>
</tr>
<tr>
<td>76</td>
<td>282.6</td>
<td>218.25</td>
<td>82.89</td>
</tr>
<tr>
<td>77</td>
<td>326.2</td>
<td>240.76</td>
<td>91.44</td>
</tr>
<tr>
<td>78</td>
<td>363.0</td>
<td>273.22</td>
<td>103.77</td>
</tr>
<tr>
<td>79</td>
<td>388.5</td>
<td>289.63</td>
<td>110.00</td>
</tr>
<tr>
<td>80</td>
<td>415.0</td>
<td>315.95</td>
<td>120.00</td>
</tr>
</tbody>
</table>
Exit and entry costs at domestic ports, \( PCENTD = PORTD \times \)
\[ \text{PECFD} \times e^{RLABD \times GRT^{0.585}} \] £

Exit and entry costs at foreign ports, \( PCENTF = PORTF \times \)
\[ \text{PECFF} \times e^{RLABF \times GRT^{0.585}} \] £

Annual entry and exit costs, \( PECOST = (PCENTD + PCENTF) \times RTPA \) £

Then the total annual port costs, \( CPORT = PDCOST + PECOST \) £

The method was validated with two container ship data
and is shown in Table 10.15. The port costs calculated
for ship A was 5.50% from the actual costs, and the ship B
was overestimated by about 12%. At the preliminary design stage
cost differences of this magnitude are acceptable and therefore
the method was adopted in the program.

10.8. FUEL OIL COSTS

The fuel oil costs were subdivided into cost of heavy
fuel oil, diesel oil and lub oil. The costs were estimated
from the weights of oil consumed at sea and port and
multiplying the weights with the cost/tonne of heavy fuel
oil, diesel oil and lub oil. The ship was assumed to bunker
at the last foreign port of call, after bunkering at the
first home port. A diesel generator of 1500 KW was assumed
to be used at sea and port for generating electricity,
running the ventilation plant etc. A 10% reserve for heavy
fuel oil was carried above the requirements.
(see also section 8.2.3. for assumptions).

Oil consumed at sea/day:

(1) Heavy fuel oil consumed/day = 162 x 0.90 x BHP x 1.10
\[ x 24/10^6 \text{ tonnes} \]
where 162 gm/hp-hr is the specific fuel oil consumption
(1) 0.90 is a factor to convert the installed horse
power, to normal continuous rating, 1.10 is the 10%
reserve fuel.

(2) Diesel oil consumed/day = 162 x AUXKW \[ x \frac{1.341}{KW-hp} x \]

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TABLE 10.15. Validation of port costs.

Distance between ports = 14000 nautical miles.

(i) Ports of call:  
<table>
<thead>
<tr>
<th>Domestic</th>
<th>Foreign</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>3</td>
</tr>
<tr>
<td>Irregular</td>
<td>(Australia)</td>
</tr>
</tbody>
</table>

(ii) PORTIME in days:  
- 4 (Japan) Australia = 8.0
- 1 (Korea) Japan = 5.3
- Korea = 1.0

(iii) Annual Costs 80-81  

<table>
<thead>
<tr>
<th>Ship</th>
<th>(TEU)</th>
<th>Cost (80-81)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1288</td>
<td>130278</td>
</tr>
<tr>
<td>B</td>
<td>1684</td>
<td>272410</td>
</tr>
</tbody>
</table>

Seatime in days = 14000/23 x 24.0 = 25.36

Round trip time in days = 25.36 + 8.825 = 34.185

No. of round trips/annum = 350/39.66 = 8.825

(iv)  

| PCOSTF | 2714 | 3409 |
| PCOSTD | 20033 | 25527 |
| PDCOST | 11373 | 14468 |
| PCENTD | 17216 | 21329 |
| PCENTF | 12656 | 15679 |
| PECOST | 29872 | 37008 |
| PDCOST + PECOST | 41245 | 51476 |
| CPORT | £363991 | £454275 |
| Actual port costs | 385191 | 405877 |
| % difference from actual costs | 5.50 | -11.92 |
0.50 load \times \frac{24}{10^6} \text{ tonnes.}

The diesel generator is assumed to be a medium speed diesel engine.

(3) Cylinder luboil consumption/day = 0.37 g/HP-hr \times \text{BHP} \times 0.90 \times 24 \times 10^6 \text{ tonnes}

(4) System luboil consumption/day = 0.26 g/HP-hr \times \text{BHP} \times 0.90 \times 24 \times 10^6 \text{ tonnes}

where the system and cylinder luboil consumption was taken from Buxton (101).

Oil consumed in port/day:

(5) Heavy fuel oil consumed/day = 24.0 \text{ tonnes}

(6) Diesel fuel oil consumed/day = 162 \text{ gm/BHP hr} \times \text{AUXKW} \times \frac{1.341}{KW} \times \frac{0.75 \text{ load}}{0.95 \text{ eff.}} \times \frac{24}{10^6} \text{ tonnes}

Cost of heavy fuel oil, diesel oil, cylinder luboil and system luboil is fed in as an input and the values for 1980 were

Heavy fuel oil, £80/tonne; Diesel oil, £145/tonne;
cylinder luboil, £560/tonne; system luboil, £470/tonne.

Cost of fuel/annum at sea

Cost of fuel/annum = \text{Days at sea per round voyage (SEATIM)} \times \text{round trips/annum (RTPA)} \times ((1) \times 80 + (2) \times 145 + (3) \times 560 + (4) \times 470) \ £

Cost of fuel/annum in port

Cost of fuel/annum = \text{Days in port per round voyage (PORTIM)} \times \text{RTPA} \times ((5) \times 80 + (6) \times 145) \ £

Total fuel oil costs per annum is the sum of the cost of fuel/annum at sea and cost of fuel/annum in port.

The heavy fuel oil and marine diesel oil costs are regularly published in (131) for some major ports. Luboil costs were ascertained from suppliers and reflect higher than average costs.
10.9. CONTAINER HANDLING COSTS

Container handling costs do not vary much from port to port. Buxton (107) gives for 1978 cost levels, the handling cost of a 20 ft. container, ship to quay, or vice versa as £40 to £60 and similarly for a 40 ft. container to be £50 to £80. These handling costs do not include stuffing and stripping the containers which will cost extra. These are not included in the sea freight, so it is not paid by the ship operator (107). A port authority contacted for 1982 costs, quoted £60 - £90 per container move. There were no charges either for the size of the container or the contents of the container and the charges in many cases depended on a particular customer.

Some ports however do differentiate between loaded and empty containers, typical values from port of Israel are, (129), at 1980 costs

<table>
<thead>
<tr>
<th></th>
<th>20' Container</th>
<th>40' Container</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>£53.21</td>
<td>£79.77</td>
</tr>
<tr>
<td>Empty</td>
<td>£25.88</td>
<td>£38.83</td>
</tr>
</tbody>
</table>

with the full containers costing twice as much. There was however no rebate on imported or exported containers.

Based on a U.K. port figure, the cost to handle a 20' container was taken as £50/container move at 1980 cost level.

The maximum load factor was calculated as the maximum of the inbound or the outbound load factor.

Then the total handling cost = number of containers carried x container handling cost/move x max. load factor x 4 x round trips/annum. The factor 2 is for loading and unloading a container and a further factor of 2 for the round voyage.

10.10. OPERATING COSTS

The operating cost elements are calculated as discussed in the previous sections. Some of these cost elements can be escalated to reflect costs in the future. The average escalation over the last 15 years is a good guideline. Such escalation rates are given in Table 10.16 (123).
Section 12.6 gives details on how the escalation rates can be introduced in the computer program. Cameron (142), Laing (143) and Buxton (101) give average escalation rates for various elements of the operating costs. Table 10.16 also gives indices of certain operating costs which can be used to update cost equations valid for different periods. Gardner (130) gives cost increases per slot (1971-76) which includes all the costs associated with container ship operation such as charges allocated to depreciation for container ships including feeder vessels, and containers and rolling stock, positioning costs, equipment leasing and operating costs etc. Thus if the inland sector of cost is to be considered these elements of costs can be updated from (130). Operating costs were validated with a limited data base, since most shipowners were reluctant to disclose even past years operating costs. However two shipping companies responded favourably and therefore the costs developed reflect the average of these two shipowners' operating costs.
<table>
<thead>
<tr>
<th>ITEM</th>
<th>1965 = 100</th>
<th></th>
<th></th>
<th></th>
<th>1971 = 100</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Av. Incr. in %/annum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>66</td>
<td>67</td>
<td>68</td>
<td>69</td>
<td>70</td>
<td>71</td>
<td>72</td>
<td>73</td>
<td>74</td>
<td>75</td>
<td>76</td>
</tr>
<tr>
<td>Wages</td>
<td>107</td>
<td>124</td>
<td>128</td>
<td>130</td>
<td>137</td>
<td>177</td>
<td>103</td>
<td>117</td>
<td>132</td>
<td>154</td>
<td>169</td>
</tr>
<tr>
<td>(6.54)</td>
<td>(13.71)</td>
<td>(3.13)</td>
<td>(1.54)</td>
<td>(5.11)</td>
<td>(22.60)</td>
<td>(2.91)</td>
<td>(11.96)(11.36)(14.28)(8.88)(12.88)(4.33)(2.87)(0.948)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other crew costs</td>
<td>106</td>
<td>124</td>
<td>133</td>
<td>135</td>
<td>148</td>
<td>202</td>
<td>112</td>
<td>132</td>
<td>156</td>
<td>185</td>
<td>195</td>
</tr>
<tr>
<td>Provisions</td>
<td>103</td>
<td>100</td>
<td>97</td>
<td>92</td>
<td>92</td>
<td>98</td>
<td>103</td>
<td>116</td>
<td>131</td>
<td>134</td>
<td>141</td>
</tr>
<tr>
<td>Stores</td>
<td>112</td>
<td>110</td>
<td>108</td>
<td>110</td>
<td>122</td>
<td>130</td>
<td>100</td>
<td>105</td>
<td>131</td>
<td>132</td>
<td>130</td>
</tr>
<tr>
<td>(0)</td>
<td>(5)</td>
<td>(19.85)(0.75)(-1.54)(10.96)(-6.57)(11.61)(8.82)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lubricating oil</td>
<td>101</td>
<td>99</td>
<td>124</td>
<td>135</td>
<td>145</td>
<td>139</td>
<td>146</td>
<td>169</td>
<td>210</td>
<td>210</td>
<td>210</td>
</tr>
<tr>
<td>P &amp; I</td>
<td>106</td>
<td>118</td>
<td>123</td>
<td>140</td>
<td>160</td>
<td>196</td>
<td>99.5</td>
<td>96</td>
<td>86.5</td>
<td>85</td>
<td>79</td>
</tr>
<tr>
<td>(93)*</td>
<td>(87)*</td>
<td>(78)*</td>
<td>(83)*</td>
<td>(83)*</td>
<td>(93)*</td>
<td>(93)*</td>
<td>(105)*</td>
<td>(105)*</td>
<td>(95)*</td>
<td>(93)*</td>
<td>(93)*</td>
</tr>
<tr>
<td>Other insurances</td>
<td>(5.66)</td>
<td>(10.17)</td>
<td>(4.06)</td>
<td>(12.14)</td>
<td>(12.5)</td>
<td>(18.37)</td>
<td>(106)*</td>
<td>(105)*</td>
<td>(95)*</td>
<td>(83)*</td>
<td>(93)*</td>
</tr>
<tr>
<td>Administration</td>
<td>111</td>
<td>108</td>
<td>115</td>
<td>126</td>
<td>143</td>
<td>182</td>
<td>104</td>
<td>115</td>
<td>141</td>
<td>166</td>
<td>174</td>
</tr>
<tr>
<td>Repair &amp; mainten.</td>
<td>111</td>
<td>110</td>
<td>138</td>
<td>132</td>
<td>166</td>
<td>242</td>
<td>91</td>
<td>95</td>
<td>121</td>
<td>107</td>
<td>83</td>
</tr>
<tr>
<td>Total</td>
<td>108</td>
<td>113</td>
<td>120</td>
<td>124</td>
<td>138</td>
<td>175</td>
<td>101</td>
<td>109</td>
<td>125</td>
<td>131</td>
<td>132</td>
</tr>
</tbody>
</table>
TABLE 10.16 (Contd.).

NOTES: (1) + calculated from 1971-1980 only,
(2) (    )% increase/annum,
(3) (    )* index for that year.
CHAPTER 11
CONTAINER COST MODEL

11.0 INTRODUCTION
11.1 NUMBER OF SETS OF CONTAINERS
11.2 CAPITAL COST
11.3 MAINTENANCE AND REPAIR COST
11.4 INSURANCE COST
11.5 LIFE OF CONTAINER
11.6 FINANCIAL MODEL
11.0 INTRODUCTION

Fairplay (132) gives an early 1981 price for a 25000 dwt, 1200 teu, 22 knots diesel container ship to be £26.12 x 10^6 excluding containers. If the ships are assumed to require 3 sets of 20' dry containers, then the cost of container sets @ £2700/teu is £9.72 x 10^6. Thus the initial ship capital cost is 73% and container costs are 27% of the total cost, nearly one third. This shows the importance of the box/slot ratio in a container ship and the overall importance of the container cost.

Independent sources estimate the world container population at the beginning of 1979 to be between 2.25 to 2.75 million teu. Of these the leasing companies own between 38 to 54%, depending on the survey one selects (133).

In any intermodal or through transport concept there are at least six major sections or operating cost centres, mainly:

(a) Inland transportation - exporting area
(b) Terminal operations - exporting area
(c) Ocean transit
(d) Terminal operations - importing area
(e) Inland transportation - importing area

but all of the above functions are subordinate to the common link throughout the system.

(f) Containers.

The containers and their associated services and cost of
(a) Systems control and coordination
(b) Storage
(c) Maintenance and repair
(d) Insurance and claim (Cargo and container)
(e) Owning or leasing of containers/associated handling equipment play a major role.

In this thesis we will neglect the inland sector of the operating costs such as storage, stuffing/unstuffing,
stripping, inland transportation and cargo insurance. This is justified in the sense that in inland transportation costs vary from country to country but the shipping costs are relatively international in nature. Though containers have introduced the concept of door to door service, when comparing the alternative ship design, if it is assumed that inland sector costs will remain the same for all ship alternatives (Inland sector costs are not associated with faster sea transit times).

The following aspects of the container costs are discussed below:

1) Container sets
2) Container Acquisition cost
3) Container Maintenance cost
   (a) Container Refurbishing cost
   (b) Container Repair cost
4) Container Insurance costs
5) Container Life

11.1. NUMBER OF SETS OF CONTAINERS (SETCNT)

Edmond & Wright (134) have published a method of estimating the total number of container sets. The model takes into account the container dwell time inland, number of ships in the fleet, ships turnaround time, number of containers loaded and unloaded etc. They found that the ratio of the number of containers required/ship slot can vary from less than 2 up to 10 or more and in most cases, it was found to be virtually independent of the number of ships in service.

Frankel and Marcus (53) gives the following equation for the number of sets of containers (SETCNT) on each end of the sealeg as

\[ \text{SETCNT} = 0.465 + 13.66/\text{FREQ} \] \text{Teu} \quad \text{Eq. 11.1}

where FREQ is the frequency of service in days.
Therefore container inventory (CNTINV) for one ship is (53)

\[
\text{CNTINV} = \text{CNT} \times \text{ALFMAX} \times (1.0 + 2.0 \times \text{SETCNT}) \text{ Teu Eq. (11.2)}
\]

CNT = container carrying capacity of the ship in Teu.
ALFMAX = maximum ship's load factor in percentage
and if FREQ is not known then it is estimated as (53)

\[
\text{FREQ} = 0.565 \times \text{RVYTIM}^{0.85} \text{ days Eq. (11.3)}
\]

RVYTIM = Round voyage time in days.

These formulae are based on statistical analysis of first generation of container ships and thus may not be valid for newer generations of container ships. Moreover Edmond & Wright (134) have shown that the number of sets of containers are dependent on many other factors, besides the ships turnaround time. Therefore such simple expressions for calculating the number of sets of containers cannot be used.

Fig. 11.1 shows the number of container sets per ship against the number of round voyages per ship per year (134). On the deep sea route the inland turnaround time \( \bar{t} \) of the container is 20 to 23 days (134, 135). As is evident from Fig. 11.1 the number of container sets/ship or box/slot ratio is very sensitive to the turn around time \( \bar{t} \) of the container. Realistic data on container berth dwell time for 5 container terminals is given by Dally et al. (136).

For numbers of round voyages per annum of 14 (137) Europe-Far East route from Fig. 11.1 the box/slot ratio varies from 2 to 3.2. Since container turn around time varies from route to route (134), and the box/slot ratio is very sensitive to the \( \bar{t} \), therefore to observe the influence of number sets of containers (SETCNT) on the overall profitability of the ship, SETCNT was left as an input data.

The most likely estimate for SETCNT is taken as 2.5 sets/ship but later in the thesis a sensitivity analysis is carried out with the optimistic estimate of 1.8 sets of container and a pessimistic estimate of 3 sets of containers.

Therefore the container inventory is given by (CNTINV)
Fig. 11.1. Box/slot ratios and number of round voyages/Year, Load Factor = 0.8 (134)
11.2. CAPITAL COST (CNCOST)

Fairplay (132) gives representative prices for 20' dry containers and 20' insulated containers. If a mix of containers are carried the total price of containers will accordingly be in the ratio of this mix.

At early 1980 prices the following figures are adopted in this thesis. Dry 20' Container (COSCNT) = £2500/unit and Reefer 20' = £3400/unit (132) and the total capital cost (CNCOST) of containers is

\[
\text{CNCOST} = \text{CNTINV} \times \text{COSCNT} \quad \text{£} \quad \text{Eq. (11.5)}
\]

The analysis in this thesis is carried out with 20' dry containers. Other specialised types of container are not taken into account, but are feasible, once the type and number of mix of containers are known. Since other associated costs like insurance and maintenance are taken as a percentage of the first cost similar equations for other types of containers can easily be developed.

11.3. MAINTENANCE AND REPAIR COST (CMCOST)

Major refurbishing of containers is undertaken to extend their life. Pentimonti (138) recommends that steel containers can be refurbished every 5 years and aluminium and FRP containers every 8 years.

In this thesis only minor refurbishing is considered and the containers are assumed to be replaced by new sets of containers after the expiry of their expected life.

Annual refurbishing or maintenance and repair costs of the containers is usually calculated as a percentage of the total capital cost of containers. Some values used in past studies is indicated below.

Butcher (139) gives absolute values of maintenance costs and repair costs for 1976 cost levels, average
number of repairs/unit/annum and the average days out of service/repair for different types of containers. For a 20' steel container average numbers of repairs/annum is 1.23, and taking the price of a 20' container as £1500 (132) gives an average repair cost/unit/annum of 5.78% and maintenance cost/unit/annum of 2.06% of capital cost. Similar calculations can be carried out for other types of containers. The annual maintenance and minor refurbishing costs/annum (COSREF) is assumed to be 1.5% of the capital cost. And the annual repair costs (COSREP) is assumed to be 6.5% of the Capital Cost.

\[
\text{COSREF} = 1.5 \times \text{CNCOST/100.0} \quad \£ \quad \text{Eq. (11.6)}
\]

\[
\text{COSREP} = 6.5 \times \text{CNCOST/100.0} \quad \£ \quad \text{Eq. (11.7)}
\]

and the annual maintenance and repair cost (CMCOST) is given by

\[
\text{CMCOST} = \text{COSREF} + \text{COSREP} \quad \£ \quad \text{Eq. (11.8)}
\]

11.4. INSURANCE COST (COSINS)

Operators often self-insure their containers or merely insure against catastrophic loss by maintaining a high deductible. The model includes a container insurance cost. The insurance cost is an average annual cost and assumed to be 2% of the capital cost (54) and is expressed as

\[
\text{COSINS} = 2 \times \text{CNCOST/100.0} \quad \£ \quad \text{Eq. (11.9)}
\]
11.5. LIFE OF CONTAINER (LIFEC)

The container life (LIFEC) forms an input data to the model. There is a lot of controversy about the probable life of different types of containers. This is evident from the following table.

<table>
<thead>
<tr>
<th>Container Type</th>
<th>Container Life in Years</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>GP</td>
<td>8-10</td>
<td>Edmonds (134)</td>
</tr>
<tr>
<td>GP</td>
<td>12-16</td>
<td>Abbott (134)</td>
</tr>
<tr>
<td>GP</td>
<td>12-16</td>
<td>Maguire (134)</td>
</tr>
<tr>
<td>Steel</td>
<td>15</td>
<td>Sherwood (140)</td>
</tr>
<tr>
<td></td>
<td>8-12</td>
<td>Brokaw (141)</td>
</tr>
<tr>
<td>Steel</td>
<td>10-12</td>
<td>Butcher (139)</td>
</tr>
</tbody>
</table>

This controversy arises because many of the containers on purpose built container ships are less than 12 years old, and therefore definitive data are not available.

In the program a container life of 8 years is assumed. Later in the thesis a sensitivity analysis is carried out for variation of container life to determine its influence on the overall profitability of the ship.

11.6. FINANCIAL MODEL

The last cost element considered in the overall model of container ship design and operation was the cost associated with the container. Therefore in addition to the operating costs, common to all ship operations, the operator of a container ship is faced with the additional cost of providing and maintaining the containers. It was pointed out that furnishing adequate numbers of sets of containers required to permit unconstrained movement of cargo involves a rather substantial investment on the part of the operator. To avoid this capital expenditure and the subsequent maintenance
costs, containers are often leased. If containers are leased, the shipowner makes an annual payment to the leaser.

Fig. 11.2 outlines the procedure followed in evaluation of the discounted cash flow for all costs associated with the container. Subroutine subprogram CONDCF is the container cost model. A short description of the procedure is given below.

In the model it is considered that the shipowner buys the containers with the help of a loan and thus the annual cost he incurs is the annual repayment of the loan, the annual maintenance and repair cost and the cost of insurance. The capital cost (CNCOST) is transformed into an equal annual sum of money.

\[ \text{CPAY} = \text{CNCOST} \times \text{CRF} \]  \( \text{Eq. (11.10)} \)

where CRF = capital recovery factor.

The interest rate (CPINT) for calculating the CRF is assumed to be 10% (135), and (141) quotes that the variation of eight year rates CPINT has been 6% per annum to over 10% per annum. Brokaw (141) also gives details of the factors governing the container purchase and leasing. A container escalation factor is assumed, ECONT(I), which takes into account the cost of replacing the containers every LIFEC years. The salvage value of the container at the end of the container life is assumed to be zero.

The annual payment is divided into the principal and the interest (CINT), where

\[ \text{CINT}(I) = \text{CNCOST} \times \frac{\text{CPINT}}{100.0} \]  \( \text{Eq. (11.11)} \)

And the Principal \( \text{CP}(I) = \text{CPAY} - \text{CINT}(I) \) \( \text{Eq. (11.12)} \)

The principal already paid is accumulated in the array CPAID(I) and the interest is charged on the remaining amount of the borrowed sum i.e.

\[ \text{CINT}(I) = \left( \frac{\text{CPINT}}{100.0} \times (\text{CNCOST} - \text{CPAID}(I-1)) \right) \]  \( \text{Eq. (11.13)} \)

The future annual repayments of the loan, i.e. interest CINT(I) and the principal CP(I) are then converted into present sum of money by converting them into present worth

275
Fig. 11.2. Container cost and financial model (Flow chart of subroutine subprogram CONDCF)

START

READ CNT, ACONT, ACMANT, ACINS LIFEC, SETCNT, CPINT LIFES, DISCNT COSCOST

COSTINV =
COST =
COSREF =
COSREP =
COSINS =
CMCOST =

I = 0
YEAR = 2.0
I = I + 1
Y = FLOAT (I-1)
YEAR = YEAR + 1
x = y + 3.0

CPAY = CNCOST x CRF
CINT (1) = ..... CP (1) = CPAY - CINT (1)
CPAID (1) = CP (1)

CINT (1) =
CP (1) =
CPAID (1) =

CNCOST =
CNCOST x ECONT(1)

CNCOST =
CNCOST x ECONT (1)
/ECONT (I-LIFEC)

CFCSL(I) =
TCFC(I) =

TCDCF = TCFC(I) + TCDCF

TCDCF =
TCINS(I) =
TCMCF(I) =

1

20

30

40

50

51

52

53

276
Fig. 11.2 (Contd.)

\[ \text{TCDCFN} = \text{TDCF} + \text{TCMDCF} + \text{TINDCF} \]

\[ \text{TINDCF} = \text{TCICF} + \text{TINDCF} \]

\[ \text{TCICF} = \text{TCIC} \times \text{PWF} \]

\[ \text{TCMDCF} = \text{TCMDCF} \]

\[ \text{I} = 1 \]
at (DISCNT) rate of discount specified in the input. Therefore the present value of the future annual repayment is

\[ TCFC(I) = CFCSL(I) \times PWF \quad £ \quad \text{Eq. (11.14)} \]

where \( CFCSL(I) = CP(I) + CINT(I) \quad £ \quad \text{Eq. (11.15)} \)

The future maintenance cost, insurance costs are similarly discounted at (DISCNT) rate of interest,

\[ TCMCF(I) = TCMCOS(I) \times PWF = \text{Present value of total maintenance cost in } I\text{th yr.} \quad \text{Eq. (11.16)} \]

\[ TCINCF(I) = TCINS(I) \times PWF = \text{Present value of insurance cost in the } I\text{th year £ Eq. (11.17)} \]

The escalation in container acquisition cost, container maintenance and repairs and the cost of insurance are input as annual escalation factor \( ACONT, ACMANT \) and \( ACINS \) respectively.

The total escalation in the \( I \)th year \( Y \) is given by \( ECONT(I), ECMANT(I) \) and \( ECINS(I) \)

\[ ECONT(I) = (1.0 + ACONT/100.0)^Y \quad \text{Eq. (11.18)} \]

\[ ECMANT(I) = (1.0 + ACMANT/100.0)^Y \quad \text{Eq. (11.19)} \]

\[ ECINS(I) = (1.0 + ACINS/100.0)^Y \quad \text{Eq. (11.20)} \]

Therefore the book value of the container cost in the \( I \)th year, otherwise the replacement cost is

\[ CNCOST = CNCOST \times ECONT(I) \quad £ \quad \text{Eq. (11.21)} \]

Similarly for the maintenance and insurance cost the escalated cost equations are

\[ TCMCOS(I) = CMCOST \times ECMANT(I) \quad £ \quad \text{Eq. (11.22)} \]

\[ TCINS(I) = COSINS \times ECINS(I) \quad £ \quad \text{Eq. (11.23)} \]

The discounting is done for the life of the ship (LIFES) which is higher than the life of the container (LIFEC).

The present value of container cost, maintenance and insurance are accumulated in \( TCDCF, TCMDCF \) and \( TINDCF \) respectively.

Therefore the present value of the container cost, maintenance and insurance is

\[ TDCFCN = TCDCF + TCMDCF + TINDCF \quad £ \quad \text{Eq. (11.24)}. \]
CHAPTER 12
ENGINEERING ECONOMY

12.0 INTRODUCTION

12.1 INTEREST RELATIONSHIPS
   12.1.1. SIMPLE INTEREST
   12.1.2. COMPOUND INTEREST

12.2 TIME ADJUSTING MONEY VALUES
   12.2.1. COMPOUND AMOUNT FACTOR AND PRESENT WORTH FACTOR
   12.2.2. CAPITAL RECOVERY FACTOR AND SERIES PRESENT WORTH FACTOR

12.3 ECONOMIC MEASURE OF MERIT

12.4 ECONOMIC COMPLEXITIES
   12.4.1. TAX
   12.4.2. INFLATION
   12.4.3. DEPRECIATION

12.5 CALCULATION OF CAPITAL CHARGE

12.6 REQUIRED FREIGHT RATE BEFORE TAX

12.7 REQUIRED FREIGHT RATE AFTER TAX
12.0 INTRODUCTION

Economics may be defined as the task of allocating a finite supply of investment funds in the face of infinite possibilities (147).

Engineering may be defined as the use of scientific knowledge for the benefit of society. Engineering economy, then, is an approach to design aimed at meeting society's needs with a maximum effectiveness in the use of resources: manpower, materials, and investment funds (147).

The goal of the engineering design process or ship design process may be defined as given a functional requirement (e.g. transportation of a certain number of containers from A to B) which also satisfies a number of constraints of technical, physical, or legal nature (stability, strength, ship safety, classification rules etc.) to seek an optimal technical solution judged on the basis of a concrete measure of merit (148).

This chapter introduces the basic principles of engineering economy calculation, the choice of measure of merit and the various other economic complexities e.g. tax, depreciation, inflation, etc. and the various assumptions made in the thesis are also indicated. Taxation, depreciation, tax allowances etc. are calculated for a shipowner building and operating his ship in the U.K.

The last three sections of the chapter gives details of calculating the builder's account, operating account and the measure of merit for a design taking into account the tax, tax allowances, depreciation, inflation and cost escalation.

The subroutine subprogram CAPCHR, ECONOM and ANPVAL can be used with little modification for other ship types.

12.1 INTEREST RELATIONSHIPS

Money has not only a nominal value, expressed in some monetary unit, but also a time value (161). Therefore the notion of time value of money is fundamental to any economic
calculation. This time value of money is usually expressed in terms of the interest, which is generally expressed as an annual charge in percent of funds invested. And this interest can be: (147)

(a) Contracted interest, is the type used in saving deposits, bank loans, mortgages and bonds which carry mutually agreed interest rates.

(b) Implied interest is also called the lost opportunity interest, which is foregone when the capital is tied up without any resulting interest being earned e.g. cargo in transit or a ship being laid up.

In this thesis only the former is taken into account. The contracted interest may either be simple or compound.

12.1.1. SIMPLY INTEREST: The total repayments after N years is expressed as \( F = P(1 + Ni) \)
where \( F \) = future sum of money; \( P \) = Principal or a present sum of money; \( N \) = number of years of loan and \( i \) = interest rate expressed as a fraction/annum.

12.1.2. COMPOUND INTEREST: This is usually the method employed for most of the economic calculation concerning ship design economics and the future repayment after N years is expressed as, \( F = P(1 + i)^N \). As far as decision making in ship design is concerned, the assumption of annual compounding is usual. Other non-annual compounding methods and their application to investment is given by Benford (149). Container financing is however done on the basis of quarterly or half yearly compounding (141). Annual compounding is assumed in all cases in this thesis.

12.2. TIME ADJUSTING MONEY VALUES

There are six basic compound interest relationships (101). Two are related to single payments and the others to series payments.

12.2.1. COMPOUND AMOUNT FACTOR AND PRESENT WORTH FACTOR: These relationships are used for single payments and is
shown in Fig. 12.1(a). The compound amount factor (CA) is the multiplier to convert a present sum into a future sum and expressed as

\[ F = (CA) \times P \text{ where } CA = (1 + i)^N \quad \text{Eq. (12.1)} \]

If the interest is compounded \( T \) times per year, with the interest rate expressed annually as \( i \), then:

\[ CA = (1 + \frac{i}{T})^{NT} \]

This relationship can be used if the containers are leased instead of being bought as assumed in this thesis, since the lease repayment is usually made half yearly or quarterly (141).

The reciprocal of the compound amount factor is the present worth factor (PW), which is the multiplier to convert a future sum into the present sum and expressed as

\[ P = (PW) \times F \text{ where } PW = \frac{P}{F} = \frac{1}{CA} = (1 + i)^{-N} \quad \text{Eq. (12.2)} \]

In the program, the PW is generated by a subroutine subprogram PREWOR given the year and the discount rate. An interest rate of 15%/annum before taxes is assumed in the thesis for discounting cash flows and is referred to as the discount rate.

12.2.2. CAPITAL RECOVERY FACTOR AND SERIES PRESENT WORTH FACTOR:

These relationships are used for series payments and is shown in Fig. 12.1(b). For a loan repaid by series of annual instalment of principal plus interest. There are two common arrangements:

(a) principal repaid in equal instalments with interest paid on the declining balance, which is used in the capital charge program to calculate the builder's account.

(b) Uniform payments, which is the usual method for leasing and mortgages, interest predominating in early years, repayment of principal in later years.

The capital recovery factor (CR) is used to convert an initial capital investment to an equivalent annual capital
Fig. 12.1a. Compound amount factor and present worth factor.

Fig. 12.1b. Capital recovery factor and series present worth factor.
charge, which includes both the principal and the interest. It is a relationship between the uniform amount \((A)\) and the principal \((P)\) and expressed as \[A = (CR \times P)\]

where \[CR = \frac{1}{1 - (1 + i)^{-N}}\]  \hspace{1cm} \text{Eq. (12.3)}

and this equation is used in the container cost model to convert the initial investment in containers to an annual capital charge repaid over the life of the container.

The reciprocal of capital recovery factor is the series present worth factor \((SPW)\) which is a multiplier to convert a number of regular annual payments into a present sum, and is given by \[P = (SPW) \times A\]

where \[SPW = \frac{P}{A} = \frac{1}{CR} = \frac{(1 + i)^N - 1}{i(1 + i)^N}\]  \hspace{1cm} \text{Eq. (12.4)}

The other two basic relationships known as the sinking fund factor \((SF)\) and its reciprocal the series compound amount factor is not used in the thesis. These relationships are given by Buxton (101) and Benford (147).

12.3. ECONOMIC MEASURE OF MERIT

The different measures of merit used in ship design studies are shown in Table 12.1. Though this is not an exhaustive list, it has been drawn up to indicate the usage of different economic measures of merit in previous design studies with particular emphasis on those concerning containerships. The popular usage of required freight rate is apparent. Buxton (101), Goss (162), Oostinjen (161), Benford (163,164), Hettena (165) give the advantages and disadvantages of the various measures of merit. Details on calculation of these measures of merit are given by Buxton (101) and Benford (163,164) or any standard textbook on capital investment (166).

Table 12.2 gives a decision chart which can be used for selecting a measure of merit, depending on the type of input data available at the design stage. Therefore
# TABLE 12.1. Summary of economic criteria and their use in past design studies.

<table>
<thead>
<tr>
<th>Economic Criteria</th>
<th>Definition (160)</th>
<th>Maximise or Minimise</th>
<th>Ship Type</th>
<th>Ref.</th>
<th>Yr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (NPV) Net present value</td>
<td>The present value of all cash flows in or out, discounted to present time at a stipulated interest rate that reflects the minimum acceptable level of profitability.</td>
<td>Max.</td>
<td>TK, VC, MP</td>
<td>150 103</td>
<td>76 82</td>
</tr>
<tr>
<td>2 (NPVI) Net present value index</td>
<td>The net present value per pound invested.</td>
<td>Max.</td>
<td>(CN+ ports) TK</td>
<td>39</td>
<td>71 72</td>
</tr>
<tr>
<td>3 (IRR) Yield or internal rate of return</td>
<td>The interest rate that brings the net present value to zero.</td>
<td>Max.</td>
<td>TK, CN</td>
<td>86</td>
<td>70</td>
</tr>
<tr>
<td>4 (RFR) Required Freight Rate</td>
<td>The unit charge to the customer that must be earned if the owner is to gain a reasonable yield on investment.</td>
<td>Min.</td>
<td>TK, PC, CN, TK, CN, CL, BC, OC, CN, BC, RO, CN, MP, OC</td>
<td>151 55 152 40 104 153 61 103 154</td>
<td>74 74 67 74 76 78 82 82 67</td>
</tr>
<tr>
<td>5 (AAC) Average Annual Cost</td>
<td>A uniform annual expense equivalent in present value to the investment and operating costs. Discounts future amounts at an interest rate reflecting the investor's time value of money.</td>
<td>Min.</td>
<td>TK, CN, CN, RO, CN, CL, CN</td>
<td>155 52 37 156 125 157</td>
<td>79 70 68 78 68 77</td>
</tr>
<tr>
<td>Economic Criteria</td>
<td>Definition (160)</td>
<td>Maximise or Minimise</td>
<td>Ship Type</td>
<td>Ref. Yr</td>
<td></td>
</tr>
<tr>
<td>---------------------------</td>
<td>----------------------------------------------------------------------------------</td>
<td>----------------------</td>
<td>-----------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>6 (PW) Present Worth</td>
<td>The present worth of both investment and operating costs. Uses same interest rate as AAC to discount future amounts.</td>
<td>Min.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(LCC) Life cycle cost</td>
<td>Same as PW</td>
<td>Min.</td>
<td>CN</td>
<td>54 72</td>
<td></td>
</tr>
<tr>
<td>7 (CC) Capitalised cost</td>
<td>The present worth of providing perpetual service.</td>
<td>Min.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 (A') Returns</td>
<td>Uniform annual after tax cash flow.</td>
<td>Max.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 (Y) Operating costs</td>
<td>Uniform annual operating costs. Marginal costs of operation, exclusive of costs of capital recovery.</td>
<td>Min.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 (CRF) Capital recovery factor</td>
<td>Ratio of uniform annual returns before tax to initial investment.</td>
<td>Max.</td>
<td>CN</td>
<td>40 74</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OC</td>
<td>62 58</td>
<td></td>
</tr>
<tr>
<td>11 (PBP) Pay back period</td>
<td>Years to regain initial investment. If cash flows are uniform, this is reciprocal of CRF.</td>
<td>Min.</td>
<td>MP</td>
<td>103 82</td>
<td></td>
</tr>
<tr>
<td>12 (SMF) Ship Merit Factor</td>
<td>Reciprocal of RFR (158)</td>
<td>Max.</td>
<td>GC</td>
<td>148 68</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>158 70</td>
<td></td>
</tr>
<tr>
<td>13 Annual costs/tonne mile</td>
<td>Total annual costs of operating the ship per ton mile</td>
<td>Min.</td>
<td>GC</td>
<td>159 81</td>
<td></td>
</tr>
</tbody>
</table>

Note: BC = Bulk Carrier; CN = Container ship; CL = Cargo Liner;
GC = General Cargo ship; MP = Multipurpose ship;
OC = Ore Carrier; PC = Products Carrier; RO = Roll on - Roll off; TK = Tanker; VC = VLCC.
TABLE 12.2. Decision chart for choice of economic criterion (101, 164, 160).

Note: Table 12.1 for definitions and abbreviations

------ connectors applicable at that particular decision level.
there is no ideal, universally applicable criterion although
the choice of the optimum itself depends on the economic
criteria (161, 164). And a measure of merit which is suitable
for finding the optimal design may fail when deciding yes
or no on the entire project. This is primarily one of the
drawbacks of RFR, since there is no point in designing a
ship with the minimum acceptable RFR when the expected RFR
are well below that level (160). Further RFR cannot be
used as a profitability criterion since it neglects the
revenue. Moreover RFR neglects demand and also fails to
take into account the supply considerations (165). In the
case of perfect competition, the freight rates will be
determined by the demand for tonnage and supply of ships.
Since a ship takes 2 to 3 years to construct, extra demand
cannot be met in the shorter term. Higher freight rates
will attract shipowners to order new ships but supply is
fixed in the shorter term. If demand does not rise then
there will be overtonnage which will force the freight rates
to fall. This cyclic behaviour in freight rate will determine
supply of ships to be ordered in the future. Hettna (165)
and Buxton (101) describe this behaviour in more detail.
Constructing such an econometric model will be quite
complicated, and it can be assumed that the required freight
rate will fluctuate between an average mean value in the
longer term (167). Though the container ship conference
system cannot be deemed as operation under perfect competition.

Oostinjen (161) carried out a comparative evaluation
of commonly used economic measures of merit, such as Net
Present Value (NPV), Capital Recovery Factor (CRF), RFR
and Absolute Profit (AP). Where AP is calculated as an
average of the real profits during the operational life of
a ship by multiplying the total present worth of the profit
by the CRF.

A sensitivity analysis of the various criteria with
uniformly increasing costs and revenues showed that the
RFR method leads to no difference in the optimal speed,
whereas AP and NPV gives higher speed optimum and CRF leads to lower optimal speed and depends on the discount rate.

Compared to other criteria the characteristics of the curve in the region of the optimum found by RFR was much flatter signifying that larger deviations from the optimum are possible. So far the salient characteristics of the Required Freight Rate has been discussed, which pointed out the various pitfalls or drawbacks of the RFR as a criterion. All criteria have some drawbacks, none of them are universally applicable as pointed out earlier, but when incomes are not predictable, as is usually the case, RFR is to be preferred as a criterion (101).

Since container ships operate under conference system, the freight rates are fixed in the shorter term and the income can be ascertained. Fig. 12.2 shows representative freight rates in the period 1977-1980. However because of the flat laxity in the region of the optimum, the optimum chosen by the RFR will not lead to a wrong decision compared to one reached by NPV or yield.

12.4. ECONOMIC COMPLEXITIES

Whereas in simple short cut studies uniform cash flows can be assumed and economic complexities like tax, depreciation and inflation incorporated (101, 160, 168, 169) in interest relationships like CR and SPW, a year by year calculation is preferred to correctly assess the influence of tax allowances such as depreciation and interests on loans. Therefore computer programs have been written for ships built under the U.K. tax regime and a shipowner utilising domestic credit terms offered by the government.

12.4.1. Tax

Taxes generally have pronounced effects on the choice of the optimum design. This is made apparent by Benford (164) where the effect of ignoring taxes leads to higher speeds by NPV and AAC and lower speed by RFR. Tax is
Figure 12.2. Average Representative Time charter Rates per Container Unit. (132)

$$/Tetu

500/800 TEU 6/12 months Time Charter

330/440 TEU 6/12 months Time Charter


289
assumed to be 52% levied on taxable profit and one year in arrears (101). Tax considerations for other countries are given by Gardner (170).

12.4.2. INFLATION

Normally in engineering studies the calculations are carried out for constant-value pounds which means that inflation or deflation is neglected. As long as a shipowner is free to adjust his freight rates to reflect his changing costs this is a reasonable assumption (164). Therefore since both income and costs are rising inflation can be neglected. However whereas other costs may well rise uniformly, depreciation allowances do not and therefore a shipowner in effect pays higher than the stipulated tax rate (160) e.g. with an assumed rate of inflation of 8% the effective tax rate which was 50% without inflation, works out to be 56.5% (171). In the program escalation in costs due to inflation can be given by either assigning absolute values of escalation rates or relative values of escalation rates. Historic data on escalation can be used as a guide line e.g. Cameron (142), Buxton (101) give escalation rates in percentage/annum for the costs as well as the income. Escalation rates of certain items of costs are indicated in Section 9.4 and Sections 10.10 and incorporation of these in the program is indicated in Section 12.6. Benford (160) gives the procedure on how to incorporate inflation when calculating in constant value pounds. Most of the parametric studies carried out in Chapter 14 are in constant value pounds without inflation.

12.4.3. DEPRECIATION

There are various types of depreciation and these are given by Buxton (101), Cameron (142). Since the economic study is carried out for a shipowner under the U.K. tax regime 'free depreciation' is assumed. Free depreciation allows the shipowner to extinguish all liability for tax
until the depreciation allowances have been exhausted (101).

12.5. CALCULATION OF CAPITAL CHARGE

After the building cost of the ship is estimated, the builder's account is calculated in the subroutine CAPCHR. It uses as input the capital cost of the ship, life of the ship, discount rate in percentage interest on loan repayment and the number of years of loan. The procedure given by Buxton (101) is followed.

The following assumptions are made:

1) The loan taken by the shipowner to finance the ship is 70% of the Capital Cost, the other 30% is the owner's own account.
2) The number of years of loan is 7 years and the interest on the loan is 12% per annum.
3) The discounting is done with a discount rate of 15% per annum.
4) Year 0 is the year contract is signed and the ship delivered in year 2.
5) Building Instalment: 30% when the contract is signed, 15% when the keel is laid i.e. year 1.5, 50% when launched i.e. year 1.75 and 5% when delivered i.e. year 2.
6) The loan is repaid in equal instalments over the period of the loan and is paid every year.

The procedure is carried out in subroutine subprogram CAPCHR and is shown in Fig. 12.3. The capital charge program calculates the builder's account. The interest payable on the loan every year is stored in an array TINT(K), to be set off against profits as tax allowances.

The present value of the Capital Cost based on the cash outflow is accumulated in BLDDCF.

Table 12.3 shows for a container ship the building account based on the above assumptions, the same procedure is followed in the algorithm. The program was validated by carrying out step by step hand calculation.
Fig. 12.3. Flow chart of capital charge program (CAPCHR).
<table>
<thead>
<tr>
<th>Year</th>
<th>Building Instalment</th>
<th>Owner's 30%</th>
<th>Loan 70%</th>
<th>Loan Repayment</th>
<th>Loan Outstanding</th>
<th>Loan interest @ 10%</th>
<th>Cash Outflow</th>
<th>PWF @ 12%</th>
<th>DCF</th>
<th>BLDDCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>OWNACT -</td>
<td>-</td>
<td>REPAYM -</td>
<td>REMAIN -</td>
<td>TINT(K) -</td>
<td>-</td>
<td>PWF 1.000</td>
<td>12.24</td>
<td>12.24</td>
</tr>
<tr>
<td>1.5</td>
<td>6.1185</td>
<td>15%</td>
<td>6.1185</td>
<td>REPAYM -</td>
<td>REMAIN -</td>
<td>0.1475 0.1475</td>
<td>0.8201</td>
<td>0.12 0.5097</td>
<td>12.3610</td>
<td></td>
</tr>
<tr>
<td>1.75</td>
<td>20.395</td>
<td>50%</td>
<td>20.395</td>
<td>REPAYM -</td>
<td>REMAIN -</td>
<td>0.6393 0.6393</td>
<td>0.7972</td>
<td>0.5097 12.8707</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.0395</td>
<td>5%</td>
<td>2.0395</td>
<td>REPAYM -</td>
<td>REMAIN -</td>
<td>0.6393 0.6393</td>
<td>0.7972</td>
<td>0.5097 12.8707</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4.079</td>
<td>-</td>
<td>24.474</td>
<td>REPAYM -</td>
<td>REMAIN -</td>
<td>2.8553 6.9343</td>
<td>0.7118</td>
<td>4.9358 17.8065</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4.079</td>
<td>-</td>
<td>24.474</td>
<td>REPAYM -</td>
<td>REMAIN -</td>
<td>2.8553 6.9343</td>
<td>0.7118</td>
<td>4.9358 17.8065</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4.079</td>
<td>-</td>
<td>16.316</td>
<td>REPAYM -</td>
<td>REMAIN -</td>
<td>2.0395 6.1185</td>
<td>0.5674</td>
<td>3.4716 25.4256</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>4.079</td>
<td>-</td>
<td>12.237</td>
<td>REPAYM -</td>
<td>REMAIN -</td>
<td>1.6316 5.7106</td>
<td>0.5066</td>
<td>2.8929 28.3185</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>4.079</td>
<td>-</td>
<td>8.158</td>
<td>REPAYM -</td>
<td>REMAIN -</td>
<td>1.2237 5.3027</td>
<td>0.4523</td>
<td>2.3984 30.7169</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>4.079</td>
<td>4.079</td>
<td>-</td>
<td>REPAYM 0.8158</td>
<td>REMAIN 4.8948</td>
<td>0.4039 1.9770</td>
<td>0.3606</td>
<td>1.6179 34.318</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>4.079</td>
<td>4.079</td>
<td>0</td>
<td>REPAYM 4.4869</td>
<td>REMAIN 0.4079</td>
<td>0.4079 4.4869</td>
<td>0.3606</td>
<td>1.6179 34.318</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Capital cost = 40.793 (CAPCOS)**

All cash in £ 1980 costs in millions ($10^6$). All dimensions in m. For the following container ship

L = 274.32; B = 32.26; T = 10.97; D = 24.60; C_b = 0.529; SHP=80000 HP; REV = 137.5 RPM.
12.6. REQUIRED FREIGHT RATE BEFORE TAX

The Required Freight Rate is the calculated freight income needed per unit of cargo to cover all operating costs and to provide the required rate of return on the capital invested in the ship and containers (101).

Since the acquisition cost of the ship and the containers, the required rate of return, all the operating costs, and the annual cargo transported are known, the level of freight rate which produces equal present worths of income and expenditure can be ascertained, i.e. zero NPV. The general form of the equation is,

\[
\text{Required Freight Rate (RFR)} = \sum_{\text{year} = 0}^{\text{year} = N} \frac{\text{PW(annual operating costs} \text{ship + containers})}{\text{PW(annual cargo quantity)}} + \frac{\text{PW(Acquisition Cost}} \text{ship + containers)}}{\text{PW(annual cargo quantity)}} \text{£/tonne} \tag{12.5}
\]

In the previous chapters we have estimated all the factors on the RHS of Eq. 12.5, therefore RFR can be calculated. Thus RFR can be regarded as a calculated long term average freighting cost, which can then be compared with actual market freight rates to ascertain that building the ship is an economic proposition or not.

Since the cash flows are not uniform, an initial freight rate is assumed so that an initial NPV can be calculated. As this NPV may not be exactly zero, an iterative procedure is adopted to find the exact freight rate which gives zero NPV.

The ship which gives the minimum Required Freight Rate (RFR) is then chosen as best design or the optimum design.

The procedure adopted in the program is explained below.

(1) The program is capable of accepting escalation in operating cost of the ship and the containers, and container cost escalation, since the life of the containers is less than the ship's life.
(2) The first estimation to RFR is calculated in the subroutine subprogram ECONOM. The taxation and the tax allowances are not considered, so this is the RFR before tax. This value of RFR is used as a first estimation of income and income tax and tax allowances, such as depreciation and interest on loan are considered in another subroutine subprogram ANPVAL.

(3) The ECONOM subroutine calls the various subroutines which calculate the weights, costs and the operating characteristics of the ship and the containers (see Fig. 13.10).

(4) The year 3 is the year of operation since year 0 to year 2 is assumed to be time taken to deliver the ship.

(5) The cargo carried per annum (CDWTPA) is given by

\[
\text{CDWTPA} = \text{CNT} \times \text{WEC} \times 2.0 \times \text{ALFMAX} \times \text{RTPA} \text{ tonnes Eq.}(12.6)
\]

where CNT is actual ship capacity in Teu, WEC is the weight of each container assuming homogeneous distribution of weights in containers, factor of 2 derives from the ability to carry one cargo outwards, another homewards, on a round trip and RTPA is the number of round trips per annum.

(6) Each of the operating cost elements can be escalated with a differing rate and the escalation in cost in a given year is given by the general formula

\[
\text{ECOST}(I) = (1.0 + \text{ARATE}/100.0)^Y \quad \text{Eq.} \,(12.7)
\]

where ARATE is the percentage rate of escalation and Y is the number of years for escalation. Following are the elements of operating cost which are assumed to be escalating at different rates.

(a) Handling Costs (AHANDL, EHANDL(I))
(b) Port Costs (APORT, EPORT(I))
(c) Fuel Costs (AFUEL, EFUEL(I))
(d) Basic Wages Crew, PO officers (AWAGES, EWAGES(I))
(e) Other Crew Costs such as cost of overtime, leave, study, security and insurance, travel and training (ACREW, ECREW(I))
(f) Victualling or Provisions Costs (APROV, EPROV(I))
(g) Store costs (ASTORE, ESTORE(I))
(h) P & I insurance (APIINS, EPIINS(I))
(i) War Risk and Hull Insurance (AWHINS, EWHINS(I))
(j) Maintenance and Repair Costs (ARMANT, ERMANT(I))
(k) Administrative Costs (AADMIN, EADMIN(I))

The escalation rate in the basic program is taken to be zero since we are comparing alternatives, but to calculate the shadow price, escalation rates must be considered. Typical values are indicated in Section 9.4 and Section 10.10.

(7) Then each of the elements of the operating costs are stored in an array after multiplying by the escalation factor for each year, which is

\[ CCOST(I) = \text{Operating Cost element} \times \text{ECOST}(I) \]  
\[ \text{Eq. (12.8)} \]

(8) These values are discounted by the equation

\[ PWCOST(I) = CCOST(I) \times PWF \]  
\[ \text{Eq. (12.9)} \]

where PWF is the present worth factor for year I, of discount rate DISCNT and calculated in subroutine PREWOR.

(9) From year 3 to the life of the ship this process is repeated until we have the present value of the running cost (DF RCOS), and the present value of the cargo carried/annum (DCFDWT).

(10) The present value of the building account (BLDDCF), Section 12.5, was calculated in the building account subroutine CAPCHR, and the present value of container cost and operating cost (TDCFCN) was calculated in the subroutine CONDCF (Eq. 11.24).

Then

\[ RFR = \frac{(TDCFCN + BLDDCF + DFRCOS)}{DCFDWT} \text{£/tonne Eq. (12.10)} \]

12.7. REQUIRED FREIGHT RATE AFTER TAX

Once the first estimation of the required freight rate is available, the program ECONOM calls another subroutine ANPVAL. As pointed out in the last section ANPVAL was an iterative procedure to determine the required freight rate for a particular design (RFRMIN) in £/tonne.
The program flow chart is shown in Fig. 12.4 and the main steps of the procedure are described below:

1. Since we know the first estimation of Required Freight Rate RFR, the annual income, AINCOM(I), in the year I can be calculated

   \[ AINCOM(I) = RFR \times CDWTPA \]  
   \[ \text{Eq. (12.11)} \]

And annual expenditure, EXPEND(I), in the year I is given by

\[ EXPEND(I) = TRCOS(I) + TCMCOS(I) + TCINS + CFCSL(I) \]
\[ \text{Eq. (12.12)} \]

Therefore cash flow before tax, CASHBT(I), is

\[ CASHBT(I) = AINCOM(I) - EXPEND(I) \]
\[ \text{Eq. (12.13)} \]

2. Up to the year of loan (LOANYR) the interest is set off as a tax allowance and the rest of the cash flow before tax is set off as depreciation. Free depreciation is assumed in the program and the depreciation allowance is used to extinguish tax liability until the capital cost of the ship is exhausted. Year I = 1, is the year of operation and is designated as YEAR = 3.0.

3. The general form of the equation of cash flow for taxable profit and tax are

   \[ \text{TAXPROF}(I) = \text{CASHBT}(I) - \text{tax allowances (interest and depreciation)} \]
   \[ \text{Eq. (12.14)} \]

   \[ \text{TAX}(I) = \text{TAXPROF}(I) \times \text{TAXPCT}/100.0 \]
   \[ \text{Eq. (12.15)} \]

where percentage of tax (TAXPCT) is an input data.

The tax (TAX(I)) is assumed to be paid one year later, and the general form of the equation for cash flow after tax, CASHAT(I), is

\[ \text{CASHAT}(I) = \text{CASHBT}(I) - \text{TAX}(I) \]
\[ \text{Eq. (12.16)} \]

At the end of life of the ship however, there will be one more tax to be paid, then for year I = LIFES + 1, the balancing charge (101, 140) assuming the scrap value to be zero is, \[ \text{CASHAT}(I) = -\text{TAX}(I-1) \]
\[ \text{Eq. (12.17)} \]
Fig. 12.4. Flow chart for calculating the minimum required freight rate.
Fig. 12.4. (Continued).
The cash flow after tax is discounted at the input discount rate (DISCNT) and is stored as

\[ \text{PWCASH}(I) = \text{CASHAT}(I) \times \text{PWF} \]  \hspace{1cm} \text{Eq. (12.18)}

where PWF is the present worth factor for the year I and is calculated in subroutine PREWOR.

The summation of all the cash flows in each year is accumulated as discounted cash flow (DCFCAS) and is the present value of all the cash flows over the operating life of the ship.

4. The net present value is then calculated as

\[ \text{CALNPV} = \text{BLDDCF} - \text{DCFCAS} \]  \hspace{1cm} \text{Eq. (12.19)}

and is the difference between the present worth of the building account, BLDDCF (Section 12.5) and the present worth of the operating account DCFCAS.

5. The procedure from step 1 to 4 is repeated for two other values of RFR i.e. 1.20 RFR and 0.80 RFR, which gives us 3 values of RFR and 3 values of NPV's, then by using an interpolating subroutine LAGINT, we calculate the required freight rate which gives the NPV equal to zero. This Required Freight Rate (RFRMIN) is the freight rate after tax which can then be compared with the actual freight rates as shown in Fig. 12.2.
CHAPTER 13

DETERMINISTIC APPROACH TO CONTAINER SHIP DESIGN

13.0 INTRODUCTION

13.1 CONTAINER SHIP CAPACITY
   13.1.1. EXISTING ESTIMATION METHODS
   13.1.2. DRAWBACKS OF EXISTING METHODS
   13.1.3. FACTORS DETERMINING UNDER DECK CAPACITY
   13.1.4. FACTORS DETERMINING DECK CAPACITY

13.2 DESIGN PHILOSOPHY OF THE APPROACH ADOPTED
   13.2.1. MAXIMUM SLOT CAPACITY
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      13.2.2.3. INFLUENCE OF DRAFT
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13.3 SEAKEEPING

13.4 PARAMETRIC METHOD

13.5 OPTIMISATION TECHNIQUES
13.0 INTRODUCTION

The container moulds the cargo to units of preset size and shape. The ship's form, being that of a curved stream line shape, cannot accommodate the modular make-up of the cargo without some loss in cargo space. This loss in cargo space can, however, be made up by stowing containers on deck. Further this inefficiency in cargo stowage in containerships compared to a general cargo ship is tolerated because of the higher handling rate of containers, thereby increasing its annual carrying capacity.

The container capacity below the deck and above the deck is to a certain extent a function of hull geometry and deck geometry of the ship. But the number of containers stowed on deck is largely a function of ship's stability. Thus stability, as opposed to geometry, of the ship plays a major role in determining the number of containers carried on deck and hence the total container capacity of the ship.

In this chapter, the different estimating methods which have been proposed in past studies are compared, and a better estimating method proposed. The notion of maximum container slot capacity and container load capacity is introduced. The stability of the container ship and the various other operating parameters which govern the container load capacity are discussed.

Since only principal dimensions of the vessel are known at the preliminary design stage, certain approximations are needed as to the distribution of the containers in the hold and the deck without recourse to ship's lines to establish the centre of the container cargo. Therefore how this can be established is described.

Statistical stability criteria and a simple seakeeping criteria which are incorporated in the program are described.

The two ship design algorithms, for determining the optimum design are then discussed. The first is based on a simple parametric variation of principal dimension to
generate large numbers of feasible designs and the optimum design is located manually by the designer by selecting one with the minimum required freight rate. The second design model is based on automatic selection of the optimum design, by application of optimization techniques. These two ship design algorithms form the stage 1 and stage 2 of the deterministic phase of the ship design respectively.

13.1 CONTAINER SHIP CAPACITY

Maximum slot capacity is defined as the maximum allowable number of containers that can be stowed based on the ship's hull and deck geometry. Whereas actual or load container capacity is defined as the maximum number of containers that can be stowed limited by a ship's stability and deadweight requirements. All empirical relationships given below estimate the maximum slot capacity.

The total container capacity of a ship can be subdivided into containers carried below deck and containers above deck. The preferred method in the past was to estimate container capacity below deck as a function of volumetric underdeck capacity and then estimate the deck capacity as a function of deck area or deck area and permissible deck loading (39,52). Or the total container capacity simply as a function of volumetric capacity of the ship (54). Some of the methods are outlined below:

13.1.1. EXISTING ESTIMATION METHODS

METHOD 1: This method assumes that the total container capacity is a linear function of cubic number (54).

\[ T_{\text{CONT1}} = 1260.687 \times \frac{CN}{1000.0}, \quad \text{Teu} \quad \text{Eq. (13.1)} \]

where \( CN = L \times B \times D/100 \text{ m}^3 \) and all dimensions are in metres and container capacity in Teu. Equation (13.1) is valid for ships of 800 to 2400 Teu.

METHOD 2: This method divides the total container capacity as below deck and above deck container capacity and estimates these as functional relations of volume under deck and deck area respectively (39,55).

\[ T_{\text{CONT2}} = 1.307 \times C_b \times \frac{CN}{1000} + 55.648 \times \frac{L \times B}{1000}, \quad \text{Teu} \quad \text{(Eq. 13.2)} \]
Equation (13.2) is valid for containers staked up to 7 tiers high below the deck, two tiers of containers on deck and for ships of 200-1800 Teu.

METHOD 3: This is similar to Method 2 above. The total container capacity is the sum of the under deck capacity, which is a function of under deck volume and deck capacity which is a function of deck area and deck loading (52).

\[
T_{\text{CONT3}} = 7.607 \times 10^{-4} x (C_b \times CN)^2 + 0.862 \times C_b \times CN + 58.0 + \frac{\text{WABV}}{\text{CDEN}} \text{ Teu}
\]

\text{Eq. (13.3)}

where weight above deck (WABV) = 791 \times \text{DKAR} + 160 tonnes and \text{DKAR} = \text{function of deck area} = L \times B \times 10^{-4} \times 10.764 \text{ m}^2.

It is assumed that each container weighs 10 to 18 tonnes (CDEN). There are no shipboard cranes and deck containers are secured to the deck with standard lashing cables.

Equation (13.3) is valid for ships of 400-2400 Teu.

METHOD 4: This method (39) estimates the container hold capacity as a function of modified cubic number (CN x CB) and the deck capacity as a function of deck area expressed as (L x B).

\[
T_{\text{CONT4}} = 3.306 \times (CB \times CN)^{0.852} + 3.380 \times 10^{-3} \times (L \times B)^{1.329} \text{ Teu}
\]

\text{Eq. (13.4)}

Equation (13.4) is valid for ships 200-1800 Teu, other factors same as Equation (13.2).

METHOD 5: This method (39) estimates the total container capacity as a function of L, B, D and prismatic coefficient C_p.

\[
T_{\text{CONT5}} = 567.275 \times 10^{-4} L^{0.984} B^{0.573} D^{1.13} C_p^{0.965} \text{ Teu}
\]

\text{Eq. (13.5)}

Validity of Eq. (13.5) is the same as Eq. (13.4, 13.2).

METHOD 6: This method (46) is based on regression analysis of ships existing in the early seventies and the total container capacity is expressed as a function of cubic
number and speed.

\[ T_{\text{CONT6}} = 8.88 \times (CN)^{1.190} \times \left(\frac{1}{V}\right)^{1.08} \quad \text{Teu} \quad \text{Eq. (13.6)} \]

where \( V \) = speed in knots.

This equation is valid for ships of 800 to 3500 Teu and speed of 20 to 35 knots.

**METHOD 7:** This method (61) estimates the container hold capacity as a function of \((L \times B \times D)\) and the container deck capacity as a function of deck area expressed as \((L \times B)\).

\[ T_{\text{CONT7}} = 7.681 \times 10^{-3} L \times B \times D + 32.614 \times 10^{-3} L \times B + 100 \quad \text{Teu} \quad \text{Eq. (13.7)} \]

For ships in Table 13.1, the container capacity was estimated by Eq. 13.1 to Eq. 13.7 and shown in Table 13.2. There was wide variation in each of these estimation methods both for containers in holds and containers carried on deck.

### 13.1.2. DRAWBACKS OF EXISTING METHODS

It seems natural to assume that the fixed dimensions of the containers will force the breadth and the depth of the ships to be fixed on the basis of structural and stacking considerations alone, taking into account constraints on beam and depth for passage through certain canals and harbours.

To a certain extent this is true, but stability requirements and individual choice seem to be as strong factors as anything else in the choice of beam and depth of the vessel. This is made apparent in Table 13.1 where the beam varies from 3.071 m. to 3.714 m/row and the depth varies from 2.038 m. to 2.843 m/container tier below the deck.

The percentage variation from actual container hold capacity as well as deck capacity is shown in Table 13.2a. It is apparent that the percentage variation is quite large in certain cases. This is because most of these
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<th>LPP in m</th>
<th>B in m</th>
<th>D in m</th>
<th>Hold</th>
<th>Deck</th>
<th>Maxm Section</th>
<th>Total</th>
<th>CR</th>
<th>CN = LxKxD/100</th>
<th>B/W in m</th>
<th>D/H in m</th>
<th>Teu U Deck</th>
<th>Teu ABV DK 2 High</th>
<th>LxR in m²</th>
<th>LxB ABV DK 2 High</th>
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306a
### TABLE 13.3 Container Distribution on Deck

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<th>L in m.</th>
<th>B in m.</th>
<th>Cont. per Tier</th>
<th>Max. Rows Below Deck</th>
<th>Max. Rows Above Deck</th>
<th>LxB in m²</th>
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<td>STRIDER CLASS</td>
<td>0.570</td>
<td>0.961</td>
<td>0.593</td>
<td>0.970</td>
<td>Aft</td>
<td>105.0</td>
<td>0.81</td>
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<td>Encouter BAY</td>
<td>0.600</td>
<td>0.978</td>
<td>0.613</td>
<td>0.832</td>
<td>Aft</td>
<td>213.36</td>
<td>0.82</td>
</tr>
<tr>
<td>HAIWAIAN ENTERPRISE</td>
<td>0.622</td>
<td>0.973</td>
<td>0.639</td>
<td>0.884</td>
<td>Aft</td>
<td>206.35</td>
<td>0.913</td>
</tr>
<tr>
<td>CP. VOYAGEUR</td>
<td>0.648</td>
<td>0.980</td>
<td>0.661</td>
<td>0.803</td>
<td>Aft</td>
<td>153.0</td>
<td>0.870</td>
</tr>
<tr>
<td>SEA WITCH</td>
<td>0.640</td>
<td>0.978</td>
<td>0.654</td>
<td>0.829</td>
<td>Aft</td>
<td>177.34</td>
<td>0.837</td>
</tr>
<tr>
<td>ACT</td>
<td>0.623</td>
<td>0.975</td>
<td>0.639</td>
<td>0.866</td>
<td>Aft</td>
<td>205.74</td>
<td>0.806</td>
</tr>
<tr>
<td>SELANDIA</td>
<td>0.545</td>
<td>0.972</td>
<td>0.561</td>
<td>0.894</td>
<td>3/4 Aft</td>
<td>257.60</td>
<td>0.733</td>
</tr>
<tr>
<td>TAEPING</td>
<td>0.570</td>
<td>0.966</td>
<td>0.589</td>
<td>0.933</td>
<td>3/4 Aft</td>
<td>192.00</td>
<td>0.716</td>
</tr>
<tr>
<td>JAPAN ACE</td>
<td>0.566</td>
<td>0.964</td>
<td>0.587</td>
<td>0.952</td>
<td>3/4 Aft</td>
<td>175.0</td>
<td>0.720</td>
</tr>
<tr>
<td>JEDDAH CROWN</td>
<td>0.590</td>
<td>0.968</td>
<td>0.609</td>
<td>0.920</td>
<td>Aft</td>
<td>104.00</td>
<td>0.861</td>
</tr>
<tr>
<td>FIERI CROSS ISLE</td>
<td>0.570</td>
<td>0.946</td>
<td>0.602</td>
<td>1.05</td>
<td>Aft</td>
<td>133.60</td>
<td>0.794</td>
</tr>
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<td>MANCHESTER VIGOUR</td>
<td>0.735</td>
<td>0.977</td>
<td>0.752</td>
<td>0.843</td>
<td>Aft</td>
<td>103.10</td>
<td>0.958</td>
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<td>EUROLINER</td>
<td>0.550</td>
<td>0.963</td>
<td>0.571</td>
<td>0.957</td>
<td>3/4 Aft</td>
<td>224.96</td>
<td>0.712</td>
</tr>
<tr>
<td>CALIFORNIA STAR</td>
<td>0.610</td>
<td>0.972</td>
<td>0.627</td>
<td>0.889</td>
<td>3/4 Aft</td>
<td>178.00</td>
<td>0.702</td>
</tr>
<tr>
<td>DART AMERICA</td>
<td>0.610</td>
<td>0.979</td>
<td>0.623</td>
<td>0.823</td>
<td>Aft</td>
<td>218.00</td>
<td>0.815</td>
</tr>
<tr>
<td>ATLANTIC MARSIELLE</td>
<td>0.637</td>
<td>0.977</td>
<td>0.652</td>
<td>0.843</td>
<td>Aft</td>
<td>154.70</td>
<td>0.781</td>
</tr>
<tr>
<td>ELBE MARU</td>
<td>0.572</td>
<td>0.969</td>
<td>0.590</td>
<td>0.913</td>
<td>3/4 Aft</td>
<td>252.0</td>
<td>0.708</td>
</tr>
</tbody>
</table>

**R.J. SCOTTS DATA**

- Fine ships carrying 40' containers: Aft - 0.85
- Full ships carrying 20' containers: Aft - 0.90
- Fine ships carrying 40' containers: Amidships - 0.80
- Full ships carrying 20' containers: Amidships - 0.83
equations were based on regression analysis of data of containerships built during and prior to the early seventies, and therefore give poor results for ships built after this date which were of larger size and higher speeds. In many cases the number of tiers of containers carried on deck are not specified, so a valid comparison is difficult. Other factors which should be taken into consideration while determining the hold and the deck container capacity are discussed in the next two sections.

13.1.3. FACTORS DETERMINING CONTAINER CAPACITY IN HOLDS

One of the strongest factors determining the hold capacity is the type and position of the machinery space. Ships with steam turbine or gas turbine machinery have smaller machinery space than ships with diesel machinery installation. The machinery space is therefore usually located well aft with generally not more than one container hold between the machinery space and the stern. With the all aft location there is no interruption of crane movement in the way of container stowage or interference of a deck house with a shore crane. Also, there is no shaft tunnel to interfere with the container stowage; therefore in containerships, the machinery is usually located aft to give increased stowage of containers. This is also made apparent by the low shape coefficient for ships with machinery 3/4 aft (see Section 13.2.2. and Table 13.4) compared with ships with machinery aft.

Other factors which have a slight influence are the size of containers and the loss in available cargo space, due to allowances between containers. This is less for 40' containers than for the 20' containers. The variable depth of double bottom along the length of the ship has also a slight influence, the required double bottom volume being dependent on ballast and fuel capacities or the ship's trade route.

In spite of all these factors, the under deck container capacity can be approximated by relating it to the ship's under deck volume - the under deck volume being expressed
as product of length, beam, depth and block coefficient or what is known as the modified cubic number.

Henry and Karsh (5) give a relationship between under deck container capacity and the modified cubic number. Taking the enclosed volume of the hull to be \( L \times B \times D \times \frac{CB}{100.0} \), it is reasonable to assume that bale capacity of the general cargo ship can be taken as 70% of the enclosed volume (30% being engine room, peaks and double bottom spaces). From this it is necessary to subtract 20% of the bale capacity, which may be assumed to be the containerisation loss. Thus 'containerised bale capacity' may be expressed as \( (0.70 \times L \times B \times D \times CB) \times 0.80 \). The bale cubic capacity of a container varies from 81% to 89% of the extreme volume (average say 85%). If 'containerised bale capacity' represents the volume of general cargo to be carried on a containership and 'container bale cubic capacity' the volume to enter one container, then it may be assumed that the ratio of the two will give a fair approximation to under deck container capacity.

\[
\text{CTHLD} = \frac{0.56 \times L \times B \times D \times CB}{0.85 \times 6.096 \times 2.438 \times 2.438} = 1.82 \text{ CN } \times \text{ CB Teu}
\]

Comparing the coefficient of Eq. (13.8) to that of Eq. (13.2), it is on the higher side; this is because of the above assumptions on the loss in cargo hold space, usable space and the available container bale cubic etc. But it shows that for actual ship's data equations of this form will give a fairly good approximation to the hold capacity and once the containerised bale capacity is established, equations of this form should be applicable for all container dimensions. An equation of this form is derived in Section 13.2.1.

13.1.4. FACTORS DETERMINING DECK CAPACITY

The containers on deck are usually correlated to deck area or area a function of length and breadth of the ship. It is, however, difficult to analyse the data to arrive
at a good functional relationship between deck area and deck capacity. This appears to be because containers are stowed above deck in either two, three or four tiers, depending on the total container weight, corner support and tie down methods used. Therefore, to establish the above deck capacity one would need to know the cargo density, corner support and tie down method used for existing ships. Moreover, the number of containers above deck is largely independent of the block coefficient and in Table 13.1 coefficient for ratio of L x B by number of container per tier varies from 24 for larger ships to 40 for smaller ships. This variation can be explained by the fact that container rows on deck may be one or two container rows more than container rows below deck as shown in Table 13.1.

It is highly desirable to be able to load containers on deck since they increase the earning capacity without increasing the ship's volumetric capacity. The extent to which they can be stowed on deck is governed by the following considerations:

a) Owner's requirement for container protection from salt water damage.

b) Container ships have large wind sail area which may have to be reduced to provide adequate statical stability, and steering response.

c) Visibility problems especially with bridge located aft.

d) If shore based cranes are used, maximum number of tiers to which container could be stacked will depend upon both the distance from the water at high tide to crane boom as well as ship's freeboard and draft. When working cargo the limiting angle of heel is limited to 5° to avoid containers jamming in cells (5). This requirement is often more severe than the seagoing requirements and will require ballast to be added on entering port or the ship goes to sea with more than the minimum GM.
e) The securing/lashing techniques become quite complex if the number of deck tiers exceeds three.

f) The hatchcovers are designed to withstand only certain loads and more than two tiers of containers usually results in heavier and smaller hatches. Weight of hatchcovers may be limited by the crane lifting capacity and smaller hatches may result in unacceptable handling time for pontoon hatches.

As is apparent from the above, many factors limit the containers on deck, foremost of which is perhaps the stability. The deck tiers of containers is limited to 4 in the program, it otherwise determines deck capacity exclusively on the basis of available deck area and stability. Later in Section 13.2.1 a formula is developed to determine deck capacity per tier solely based on deck area and then an iterative procedure is followed until the minimum GM and statical stability is satisfied.

13.2 DESIGN PHILOSOPHY OF THE APPROACH ADOPTED

For all containerships the design deadweight is obtained at a draft less than that obtainable with a type B freeboard. Also, since a large percentage of cargo is carried on deck, it is not possible to base the design on volume requirements (35). As shown in Fig. 13.1, most container ships acquire their design deadweight at B/T ratio lower than 3.15. This is because of the beam and draft restrictions of the Panama Canal for larger ships and the deadweight requirements are achieved at drafts lower than the scantling draft for smaller ships.

However, a container ship has unlimited stowage space in the vertical direction. The stacking height may be limited by nautical consideration, seakeeping, lack of adequate lashing arrangement or by stability. A ship with maximum stability would be able to increase the number of container tiers within the limits of deadweight requirements or draught
Fig. 13.1. Beam versus design draft.

- B/T = 2.25 lower limit due to resistance and powering consideration
- B/T = 3.15
- B/T = 3.75 upper limit due to resistance and powering consideration

Draft design in m.

Breadth in m.
limitations. To obtain the actual container capacity involves the solving of a stability problem in the sense that the righting arms must be maximised. This can be done either by increasing the ship's form stability, or by providing the necessary ballast either water or permanent in the lower part of the hull. In practice some ballast is carried even in load conditions.

The design problem can be best illustrated by Fig. 13.2 (36) which shows the number of containers that can be carried at a certain draft without ballast, satisfying the minimum stability requirements. Further, as shown in the figure, more containers can be carried with ballast than without ballast. With increase in draft, displacement increases, since all the other deadweight items other than cargo remain constant the average weight per container increases. On a ship of an optimum design* the maximum permissible draft for a given average container weight is reached, the container slots are fully utilised (including available deck containers stowing) and the available ballast capacity is adequate.

However two more problems still remain which are fundamental to container ship design. These are,

(a) Should a containership be designed with homogeneous cargo loading? If so what are the practical values of weight in each container? Alternatively if it is designed with a non-homogeneous cargo loading, what should be the weight of each container from the bottom tiers up to the top tiers?

(b) If the weight of each container is fixed at a particular value, this would enable the designer to optimise the design draft. Alternatively if the weight of each container is not fixed how does one optimise the design draft?

It is possible to design containerships with maximum container loading of 20 tons provided the number of tiers in the hold does not exceed 6, e.g. Maersk ships of 1200 Teu with rated container loading of about 20 tons each (172).

*The word optimum here is not used in context of a ship chosen based on economic optimisation, but merely refers to the ship which technically will be able to carry the maximum cargo.
Fig. 13.2. Influence of draft, GM, and ballast on the containership capacity (36).
The OCL container ships were also designed assuming homogeneous loading and the average design draft was selected for a mean deadweight figure (19).

Thus for the first generation and possibly the second generation of purpose built container ships the stability was calculated on the basis of an average container weight (abt. 10-14 tons each) assuming homogeneous loading sometimes with about 10-20% of deadweight as water ballast.

In operation, however, often a considerably lower centre of gravity of the ship was ascertained as a consequence of non-homogeneous container load, leading to high GM-values with the consequence of short rolling periods (13, 173). These short rolling periods combined with high amplitudes due to the fine lines of container ships, gave disagreeable rolling motions. And the reduction of ballast water for improvement of rolling conditions has not yet led to a fully satisfactory solution (13, 173).

In order to overcome these problems and also to take into account that in actual operation, it is only the two or three lowermost tiers of containers in holds that carry the maximum rated load with progressive decrease in container weight up to the topmost tier of containers on deck which are possibly empty, most ships are designed today for non-homogeneous container load.

Following are some indicative GM-values on design for the drafts (13).

<table>
<thead>
<tr>
<th>GM m.</th>
<th>TEU</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>700-800</td>
</tr>
<tr>
<td>0.40 - 0.45</td>
<td>1200-1500</td>
</tr>
<tr>
<td>0.30</td>
<td>2300-3000</td>
</tr>
</tbody>
</table>

To resolve some of the issues regarding container ship design a leading German ship builder was approached for guidance (174). Following are the conclusions that can be drawn about container ship design.
(a) The average weight of containers and the shipping companies stowage practice is of greatest importance for the layout of container ships, depends on the type of cargo and differs from leg to leg of the ship's route. Most shipowners design their ships under the assumption of homogeneous stowage, e.g. Danish shipowners normally specify 10t/Teu whereas German shipowners tend to specify higher average weights of 13t/Teu or more. Reefer containers will have much higher average weights per Teu.

(b) It is not realistic to base the design on a fixed container weight nor can an optimization process be done by using RFR-criterion exclusively.

The purpose of a container ship should be focussed as a part of a major aim which is related to a widespread transportation task.

Therefore the design process as illustrated before in Fig. 13.2 was used for a 205 m. containership assuming homogeneous loading and is shown in Fig. 13.3. The diagram gives the number of containers of a certain weight, the corresponding draft, the possible number of containers on deck and the amount of ballast water which is needed to keep the stability on a certain level of GM.

With regard to 'built in' capabilities, Fig. 13.3 stipulates a 'field of interest' which should be reached under all anticipated loading conditions. This is shown to be between average container weight of 10t to 14t and depending on the water ballast between 8.5 m. and 11.0 m. of draft.

As pointed out earlier selected stowage of containers is usual and has to be taken into account. This is illustrated by the double hatch lines, and less ballast water will be needed. Selected stowage is a typical operational problem and can be undertaken for a few competing designs.

For selection amongst large numbers of feasible designs, a homogeneous loading is assumed and a possible range of average weight per container. Optimum design draft in most
Fig. 13.3. Total container capacity versus draft for a 205 m. container ship.
cases will be the upper limit of this average weight per container, (see Chapter 14). A few competing designs in the region of the optimum can then be studied with selected stowage of containers. This procedure ensures a certain flexibility in design which is desirable since a ship designed for a certain route and cargo characteristics will not operate on the same route for the whole period of ship's life, and route conditions may alter.

13.2.1. MAXIMUM SLOT CAPACITY

To determine the maximum slot capacity, two empirical equations are suggested. Once the maximum slot capacity of a ship is determined, the next step is to incorporate both initial and large angle stability criteria so that actual load capacity can be determined. The designer inputs the operating parameters such as route particulars and loading conditions. The program then determines the actual container load capacity until the stability requirements are met. This procedure is done in subroutine subprogram STABIL.

A good starting point in defining the upper limit to number of deck tiers is to imagine that the container stowage in the midship section is a square i.e. the number of rows of containers should be equal to the number of tiers, including deck tiers of containers. Thus, if container rows are 8 then containers are stacked 6 tiers high below deck and 2 tiers high above deck, or 5 tiers under deck and 3 tiers on deck. The proportion will be determined by the depth. If the ship is to carry permanent or water ballast or empty tiers of containers, the number of container tiers can be greater than container rows (175).

First approximation to under deck capacity

For large number of container ships modified cubic number (cubic number, CN x block coefficient, $C_b$) was fitted against the bale cubic of under deck capacity as shown in Fig. 13.4 so that container ships carrying different
sizes of containers could be converted into a common denominator.

A straight line equation was of the form (47 data points)

Bale cubic capacity (hold) = 44.21 x CN x Cb + 148.0 m³ Eq. (13.8)

There was hardly any improvement in the sum of the differences squared (an indication of the closeness of fit of data to a curve) even up to a 7th order polynomial, a straight line was adopted.

If the containers are 20' ISO standard then dividing Eq. (13.8) by one container bale cubic (20' x 8' x 8' x 0.0283 x 0.88) gives the following equation

Containers in Hold CTHLD = 1.39 x CN x Cb + 5 Teu Eq. (13.9)

This equation is valid for ships with total container capacity < 2000 TEU.

For ships of total container capacity > 2000 Teu (34 data points)

Containers in hold CNTHLD = 1.28 x CN x Cb + 220 Teu Eq. (13.10) with correlation of 0.773.

Container hold capacity for container size other than 20' ISO can easily be derived from Eq. (13.8). This is one of the main differences between this equation and those proposed earlier.

First approximation to above deck capacity

Since there is an interest in, at this stage, maximum slot capacity allowable by the hull geometry, the deck area can be represented as a function of product of length and breadth of the vessel. Table 13.3 shows the coefficients derived by dividing the actual deck container capacity per tier by length and beam of the ship, with machinery aft and machinery 3/4 aft.

Since the coefficients for ships with machinery 3/4 aft and amidships are higher than those with machinery aft, higher numbers of containers/tier can be stowed for ships with machinery 3/4 aft and amidships. Whereas the number of containers lost under deck and indicated by the shape
<table>
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<th></th>
<th>Below Deck</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Above Deck</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tier 1/2</td>
<td>Tier 3/4</td>
<td>Tier 5/6</td>
<td>Tier 7/8</td>
<td>Tier 9/Total</td>
<td>Tier 1</td>
<td>Tier 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>1. MANCHESTER CHALLENGE</td>
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<td>76/78</td>
<td>80/80</td>
<td>452</td>
<td>80</td>
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</tr>
<tr>
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<td>Calculated</td>
<td>61/65</td>
<td>71/83</td>
<td>83/83</td>
<td>446</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>2. CP VOYAGEUR</td>
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<td>84/90</td>
<td>90/90</td>
<td>503</td>
<td>108/96</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
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<td></td>
<td>Calculated</td>
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<td>79/82</td>
<td>82/82</td>
<td>463</td>
<td>124/124</td>
<td></td>
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<td>3. SEA WITCH</td>
<td>Actual</td>
<td>76/96</td>
<td>100/108</td>
<td>116/116</td>
<td>612</td>
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<td>129/129</td>
<td>662</td>
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<td></td>
<td></td>
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<td>4. ACT</td>
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<td>129/129</td>
<td>135/139</td>
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<td>126/133</td>
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<td>5. SELANDIA</td>
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<td>120/170</td>
<td>206/232</td>
<td>250/256</td>
<td>258/1662</td>
<td>305/305</td>
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<td>212/1714</td>
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<td>104/126</td>
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<tr>
<td>7. JEDDAH CROWN</td>
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<td>8. FIERY CROSS ISLE</td>
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<td>54/62</td>
<td>68/72</td>
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<td></td>
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<td>59/61</td>
<td>65/71</td>
<td>71</td>
<td>256</td>
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<td>140/170</td>
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<td>116</td>
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<td>144</td>
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<td>190</td>
<td>191</td>
<td>191</td>
<td>1562</td>
<td>273</td>
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</table>

**TABLE 13.5 (Contd.)**
coefficient, as shown in Table 13.4, is lower for ships with machinery amidships and 3/4 aft.

A containership with machinery amidships, or 3/4 aft, stores containers both in holds and on deck forward and aft of the machinery space. The aft position under deck being finer, results in more containers lost per tier. Whereas on deck the superstructure is more compact and there is more usable space aft of the ship besides housing the deck machinery. With a container ship with machinery aft under deck, capacity increases due to more containers per tier, but the space remaining after housing the deck machinery and a longer superstructure results in a lower number of containers/tier on deck.

A reasonable first estimate of the containers on deck per tier is:

\[ \text{CTDCK} = 0.0355 \times L \times B - 15.0 \text{ Teu} \quad \text{Eq. (13.11)} \]

with correlation of 0.96. Correlation of 1.0 being a perfect fit. Therefore maximum slot capacity \( \text{CNT} = \text{CNTHLD} + (\text{CTDCK}) \times \text{tiers above deck} \text{ Teu} \quad \text{Eq. (13.12)} \)

13.2.2. ACTUAL LOAD CAPACITY

Once the maximum slot capacity of the vessel is determined from Equation (13.12), the actual load capacity will depend on the operational parameters, i.e. draft, required initial GM and endurance of the vessel. Approximate volume of the double bottom is determined and depending on the volume required to store the oil fuel in double bottom, rest of the space can be taken up as ballast to improve the GM.

Shape coefficient (CSHAPE): shape coefficient is defined as the ratio of the total number of containers that can be carried in a ship shaped block to the total number of containers that can be carried in a rectangular block of the same dimensions as the ship's shape. The values of shape coefficient for some actual ships are given in Table 13.4. The shape coefficient suggested by Scott (58) and
Chryssostomidis (37) were found to be high particularly for ships with machinery 3/4 aft or amidships. This coefficient must be influenced by Froude number as well as the position and type of machinery. Some effort was made to express it in these terms but the correlation of shape coefficient expressed as a function of the speed length ratio $V/\sqrt{L}$ gave poor results. For machinery 3/4 aft or amidships

$$\text{CSHAPE} = 1.4805 - 0.8715 \times V/\sqrt{L} \text{ ft}$$ (16 data points, correlation -0.730)

For machinery aft

$$\text{CSHAPE} = 1.1788 - 0.4168 \times V/\sqrt{L} \text{ ft}$$ (18 data points, correlation -0.4168)

(See Appendix 4 for values of shape coefficient and container stacking characteristics of container ships). Great accuracy is not needed in determination of the shape coefficient (CSHAPE). The following values were adopted in the program and found to be adequate in predicting the number of bays and the loss in number of containers.

<table>
<thead>
<tr>
<th>$L_{BP}$ m.</th>
<th>$L_{BP} \leq 150$</th>
<th>$150 &lt; L_{BP} \leq 175$</th>
<th>$175 &lt; L_{BP} &lt; 200$</th>
<th>$L_{BP} \geq 200$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSHAPE</td>
<td>0.91</td>
<td>0.86</td>
<td>0.82</td>
<td>0.72</td>
</tr>
</tbody>
</table>

**Container distribution**

To calculate the vertical centre of gravity of the container cargo, distribution of the container in the hold and deck is required. This in turn requires the shape of the hull form and a procedure to estimate the number of containers in each bay along the length of the ship for every tier of containers in hold as well as on deck.

To find the number of containers stowable in holds taking into account the hull curvature from among the combinations of every conceivable principal dimensions is a
difficult task. Therefore the best hull form to suit the required speed and propulsion power is prepared first and then the number of containers stowable are estimated geometrically (176). Otherwise for a standard hull form e.g. series 60 or BSRA, the container distribution is estimated (103).

However at the preliminary design stage a precise distribution of containers is not required as long as the vertical centre of gravity can be estimated fairly accurately.

Therefore the procedure adopted in the program calculates container distribution without recourse to ship's lines fairly accurately and also gives a good approximation for the vertical centre of gravity.

For a ship of given depth and beam, the number of container tiers below deck (TIERB) and the number of rows of containers athwartships (ROWS) can be determined from Fig. 13.5 and Fig. 13.6 respectively, or by calculating the double bottom height, deck plating width and taking into account appropriate allowances for container stacking.

Watson and Gilfillan (35) give the ROWS and TIERB values as shown in Fig. 13.7 for a given number of containers in hold and speed.

For larger ships Buxton (15) gives ROWS x TIERB values. In the program ROWS and TIERB values are fed in as input data by the user. Various combinations of ROWS x TIERB values are possible, the most economic one is chosen. The number of rows (ROWS) can be varied from 6 to 10 and number of tiers under deck (TIERB) can be varied from 5 to 9. The number of tiers on deck (TIERA) are initially assumed to be 4. If CNT Eq. (13.12), is the number of containers to be accommodated, then the container bays (BAYS) is estimated by Eq. (5.14,5.15) Section 5.4.

The total number of containers lost due to hull shape (NCLOST) = CNRI - CNT

Further it is assumed that,
Fig. 13.5. Length versus depth and the container stacking in tiers.

Minimum depth
No. of tiers = 8

L/D = 10 lower limit due to structural strength consideration

Minimum depth
No. of tiers = 7

Minimum depth
No. of tiers = 6

Minimum depth
No. of tiers = 5

L/D = 14.5 upper limit due to structural strength consideration

Minimum depth
No. of tiers = 4
Fig. 13.6. Length versus breadth and container stacking in rows.
Fig. 13.7. Container distribution of the midship section (35).

Rows x Tiers values

Bounds within which these arrangements are possible.

Number of containers under deck in TEU.

Speed in knots

328
(i) The integer part of 30% of lost containers is from tier 1, NLOST1.

(ii) The integer part of 26% of lost containers is from tier 2, NLOST2.

(iii) The integer part of 20% of lost containers is from tier 3, NLOST3.

(iv) The integer part of remaining lost containers are uniformly lost from remaining upper tiers.

This assumption was validated with some actual container ship distribution and is shown in Table 13.5. Though the results are not in close agreement, it is good enough as a first approximation to determine the vertical centre of gravity of the loaded containers.

A simpler approach is given by Volker et al. (61).

The number of containers in one tier (NCONT) is assumed to be

\[ NCONT(\text{one tier}) = L \times B \times 0.0352 \text{ Teu} \]

The equation gives very high values of containers in one bay. To determine the movement of containers above and below deck, the containers in bay per tier are multiplied by the average weight of each container and its distance from the keel.

The whole procedure is shown in Appendix 2 and is carried out in subroutine subprogram STABIL and described briefly here. The metacentric height is the difference between the vertical location of the metacentre and centre of mass. The metacentre is largely a function of hull geometry and can be established from the principal dimensions. The problem of estimating the container capacity then becomes one of iterative procedure in which containers are added to or subtracted from the deck stowage until the minimum stability requirements are met. A ship with maximum stability would be able to increase the number of container tiers, which would allow the hull to be shortened within the limits set by the deadweight requirements or draft limitations (36). Thus to maximise the number of containers
that could be carried on deck the deadweight moment must be maximised without impairing the ship's operational qualities. (i) The moment contribution of miscellaneous weights \((WTMISC)\) (Section 8.2.2) is,

\[
F_{MMISC} = F_{KG} x W_{TMISC} \ m. \text{tonnes} \quad \text{Eq. (13.13)}
\]

where \(F_{KG}\) the vertical centre of gravity of miscellaneous items (see Section 8.2.2).

(ii) Moment of the oil fuel in the double bottom \((FMFB)\)

\[
F_{MFB} = F_{KGFB} x W_{FB} \ m. \text{tonnes} \quad \text{Eq. (13.14)}
\]

for weight and centre of gravity see Section 8.2.3.

(iii) Moment of the oil in settler tank \((FMFD)\)

\[
F_{MFD} = F_{KGFD} x W_{FD} \ m. \text{tonnes} \quad \text{Eq. (13.15)}
\]

for weights and centre of gravity see Section 8.2.3.

(iv) Moment of ballast if required

\[
F_{MBAL} = BALAST * FKGBAL \ m.\text{tonnes} \quad \text{Eq. (13.16)}
\]

for weight and centre of gravity see Section 13.2.2.5.

(v) Moment of lightship weight

\[
F_{ML} = FKGLTW \times W_{TLT} \ m. \text{tonnes} \quad \text{Eq. (13.17)}
\]

for weights and centre of gravity see Section.

(vi) Moment of containers below deck is calculated as follows:

Total number of containers lost from tiers one to three

\[
N_{123} = N_{LOST1} + N_{LOST2} + N_{LOST3}
\]

(See Appendix 2 for flow chart)

Let \(N_{PLAY} = \frac{NCLOST - N_{REM}}{N_{123}}\)

If \(N_{PLAY}\) is an integer, it represents the number of containers lost from each of the remaining tiers, i.e.

- tier 4, tier 5 ......tier \((TIERS-1)\), tier(TIERS)

If \(N_{PLAY}\) is not an integer, the integer part of \(N_{PLAY}\) represents the number of containers lost from tier 5, tier 6
- tier(TIERS) and the number of containers lost from tier 4, \(N_{LOST4}\) is given by

\[
N_{LOST4} = N_{PLAY} + N_{REM} - N_{REMA}
\]
where NREMA is the integer part of NPLAY multiplied by NREMV. The number of containers (CONT(I), I = 1, TIERS) is now determined as follows:

\[
\begin{align*}
\text{CONT}1 &= \text{ROWS} \times \text{BAYS} - \text{NLOST1} \\
\text{CONT}2 &= \text{ROWS} \times \text{BAYS} - \text{NLOST2} \\
\text{CONT}3 &= \text{ROWS} \times \text{BAYS} - \text{NLOST3} \\
\text{CONT}4 &= \text{ROWS} \times \text{BAYS} - \text{NLOST4}
\end{align*}
\]

The remaining layers of the number of containers in tier 5 to TIERS is given by

\[
\text{CONT} = \text{ROWS} \times \text{BAYS} - \text{NPLAY}
\]

Number of containers in the hold and deck is then given by,

\[
\begin{align*}
\text{CTHLDA} &= \text{CONT}1 + \text{CONT}2 + \text{CONT}3 + \text{CONT}4 \times (\text{TIERS-4}) \\
\text{CTDCKA} &= \text{CNT} - \text{CTHLDA}
\end{align*}
\]

This assumed number of deck containers is checked against the number of containers calculated by Eq. (13.11) termed as CTDCKC.

If CTDCKC the calculated number of containers is greater than the assumed number of containers given by CTDCKA, then the number of containers lost per layer is increased until the difference between the calculated number of deck containers and the assumed number of deck containers is less than five. Similarly if the CTDCKC is less than CTDCKA, the containers lost per layer is decreased until the difference between them is less than five containers.

If the containers in the 4th tier are greater than the containers in the 5th and subsequent tiers, the hold container capacity is

\[
\begin{align*}
\text{CTHLDC} &= \text{CONT}1 + \text{CONT}2 + \text{CONT}3 + \text{CONT}4 + \text{CONT} \times (\text{TIERS-4}) \\
\text{CTHLDC} &= \text{CONT}1 + \text{CONT}2 + \text{CONT}3 + \text{CONT}4 \times (\text{TIERS-4}) \\
\text{CTHLDC} &= \text{CONT}1 + \text{CONT}2 + \text{CONT}3 + \text{CONT}4 \times (\text{TIERS-4})
\end{align*}
\]

where containers in the subsequent tiers 4, to TIERB is given by

\[
\begin{align*}
\text{CONT}4B &= \frac{\text{CONT}4 + \text{CONT} \times (\text{TIERS-4})}{(\text{TIERS-3})}
\end{align*}
\]

The lever arm for first tier of containers is

331
ARM1 = BASE + CH/2 m, where CH = container height, assumed in the program as 2.4384 m. and the subsequent levers, ARMI = ARM1 + 2.4384 m. and BASE = double bottom height, Eq. (5.7) + Centre strake thickness, Eq. (5.8) + doubler thickness (25 mm).

The moment of containers in each tier is then

CMBT = container each layer (CONT1) x weight of each container (WEC) x the lever arm (ARM1) tonnes m. and the total moment of containers below deck (CMB) is the summation of all these moments.

Moment of containers above deck.

The lever arm (ARMA) is given by

\[ ARMA = BASEA + \left( \frac{TIERA \times CH}{2} \right) \text{ m.} \]

where container height CH is 2.4384 m; TIERA = number of tiers of containers above deck and BASEA is given by

\[ BASEA = \text{Depth at side (D)} + \text{Camber (Section 5.3(d))} + \text{Height of hatch coaming (Section 5.3(e))} + \text{Depth of the hatch cover (Table 5.4, assumed to be 500 mm)} \text{ m.} \]

The moment of containers above deck (CMA) is

\[ CMA = ARMA \times CTDCKC \times WEC \text{ tonnes m.} \]

(vii) The total moment of containers above and below the deck (FMC) is the sum of moment below deck (CMB) and the moment above deck (CMA).

\[ FMC = CMA + CMB \text{ tonnes m.} \quad \text{Eq. (13.18)} \]

(viii) The centre of gravity of the ship (FKG) in the loaded departure condition is

\[ KG = FML(\text{Eq. 13.17}) + FMC(\text{Eq. 13.18}) + FMMISC(\text{Eq. 13.13}) \]
\[ + \text{FMFB}(\text{Eq. 13.14}) + \text{FMFD}(\text{Eq. 13.15}) + \text{FMBAL}(\text{Eq. 13.16}) \text{ m} \]

the centre of buoyancy above the keel (KB) and the distance of the transverse metacenter from the centre of buoyancy (BM_T) is approximated by (86, 177, 120).
\[
\begin{align*}
KB &= \frac{1.0 + 2.0 \times C_b \times T}{1.0 + 5.0 \times C_b} \quad \text{m.} \quad \text{Eq. (13.20)}
\end{align*}
\]

and \( BM_T = \frac{K_T}{T} \frac{B^2}{T} \quad \text{m.} \quad \text{Eq. (13.21)} \)

where \( T = \) design load draft in m. and \( K_T \) may be of the form

or \( K_T = C_w (0.17 C_w + 0.13)^2 / C_B \).

Erichsen (39) gives separate relationships for single screw and twin screw ships of \( KB \) and \( BM_T \) based on regression analysis of data charts of Comstock (85). At drafts other than load draft, the values of \( KB \) and \( BM_T \) are given by Volker (61). Validity of the equations given by Erichsen and Volker were

\[ 0.92 < C_m < 0.98; \quad 0.68 < C_p < 0.78; \quad 0.63 < C_b < 0.85 \]

In this study however, ships of block coefficient less than 0.63 were considered therefore the equations of \( KB \) and \( BM_T \) of either Erichsen or Volker could not be used.

The height of the transverse metacentre above keel \( KM_T \) is

\[
KM_T = KB + BM_T \quad \text{m.} \quad \text{Eq. (13.22)}
\]

If the value of \( KG \) is greater than the value of \( KM_T \) calculated the number of containers on deck is decreased by one and the value of \( KG \) recalculated (see Appendix 2) until the value of \( KG \) is less than the value of \( KM_T \).

The transverse metacentric height \( GM_T \) is then given by

\[
GM_T = KM_T - KG \quad \text{m.} \quad \text{Eq. (13.23)}
\]

The required value of the transverse metacentric height \( *GM_T \), which is fed in as an input data is compared with \( GM_T \). An iterative procedure is followed whereby the number of containers on deck are incremented or decremented by one until the difference between the required metacentric height \( GM_T \) and the calculated \( GM_T \) is less than 0.02 m. This then gives us the total container capacity of a container ship in the loaded departure condition.

The subroutine subprogram STABIL was validated with some actual ship data, for which the operational data, container distribution, some hydrostatic particulars and in a few cases loaded departure condition were available. The program

*The required value of \( GM_T \) is denoted by \( GM_T \).
results and the actual data are shown in Table 13.6, assuming an initial GM value of 0.15 m. The values of under deck capacity gave reasonable results. It was difficult to validate the total container capacity since operational data were not fully available. Also the deck capacity mentioned in the trade journals is really the maximum slot capacity based on available deck space whereas in the program the limiting criteria was the stability and the available deck space. Therefore no valid comparison could be made with the deck capacity.

13.2.2.1. Initial stability

As mentioned earlier in Section 13.2 containerships should be designed with homogeneous container loading at the preliminary stage. This however may lead to high GM values with the consequence of short rolling periods in operation because of non-homogeneous container load. Since the container ships carry high deck load these would be exposed to damaging acceleration forces in case the rolling period became too short (39). At the same time they must have a reasonably high GM value when being loaded or unloaded lest the container get stuck in the cell structure (39, 58).

These two requirements cannot be met without the use of ballast tanks and stabilisers (39). In case of container ships sailing with metacentric height of 0.3 m to 0.9 m, active stabilisers are not necessary (178, 13), but passive stabilisers may be fitted. In such a case the ballast water is used to improve the stability of the vessel. It was also pointed out that selected stowage was an operational problem and at the design stage it will be adequate if sufficient ballast capacity is provided. Indeed Taggert (27), based upon an analysis of existing container ships, now in service suggests that at the preliminary design stage a $\frac{G_M}{B}$ value of equal to or greater than 0.025 should be ensured and it is reasonable to assume that an adequate operational $G_M$ can be maintained by filling the segregated ballast double bottom tanks as
<table>
<thead>
<tr>
<th>Ship's Name</th>
<th>Cont. Max. Slot</th>
<th>Cont. Max. U Load</th>
<th>Cont. ABV Dk.</th>
<th>From Journals</th>
<th>Containers on Deck</th>
<th>Program Results</th>
</tr>
</thead>
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<td></td>
<td>Cont. Load</td>
<td>Cont. U Dk</td>
<td>Cont. ABV Dk.</td>
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<td>B</td>
<td>LxB</td>
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<td>-</td>
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<tr>
<td>2. JAPAN ACE</td>
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<td>468</td>
<td>351(3)</td>
<td>730</td>
<td>496</td>
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<tr>
<td>3. GOLDEN GATE BRIDGE</td>
<td>800</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4. HAKONE MARU</td>
<td>851</td>
<td>851</td>
<td>472</td>
<td>379</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5. AMERICAN MARU</td>
<td>716</td>
<td>716</td>
<td>488</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6. ENCOUNTER BAY</td>
<td>1572</td>
<td>1269</td>
<td>774</td>
<td>798(4)</td>
<td>1300</td>
<td>770</td>
</tr>
<tr>
<td>7. ACT 1</td>
<td>1294</td>
<td>1294</td>
<td>696</td>
<td>598</td>
<td>1223</td>
<td>768</td>
</tr>
<tr>
<td>8. ELBE EXPRESS</td>
<td>1068</td>
<td>-</td>
<td>642</td>
<td>426</td>
<td>736</td>
<td>228(2)</td>
</tr>
<tr>
<td>9. SEA WITCH</td>
<td>928</td>
<td>-</td>
<td>612</td>
<td>316(2)</td>
<td>928</td>
<td>612</td>
</tr>
<tr>
<td>10. MANCHESTER CHALLENGE</td>
<td>542</td>
<td>542</td>
<td>456</td>
<td>86(1)</td>
<td>502</td>
<td>452</td>
</tr>
<tr>
<td>11. SEA FREIGHT LINER</td>
<td>218</td>
<td>218</td>
<td>162</td>
<td>56</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12. STRIDER CLASS</td>
<td>299</td>
<td>128</td>
<td>171(3)</td>
<td>105.00</td>
<td>16.75</td>
<td>1758.75</td>
</tr>
<tr>
<td>13. CP VOYAGER</td>
<td>779</td>
<td>779</td>
<td>593</td>
<td>276</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>14. SELANDIA</td>
<td>2512</td>
<td>2300</td>
<td>1662</td>
<td>850(4)</td>
<td>2272</td>
<td>1662</td>
</tr>
<tr>
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<td>856</td>
<td>538(3)</td>
<td>-</td>
<td>1394</td>
<td>856</td>
</tr>
<tr>
<td>16. JEDDAH CROWN</td>
<td>330</td>
<td>330</td>
<td>198</td>
<td>-</td>
<td>318</td>
<td>198</td>
</tr>
<tr>
<td>17. FIERY CROSS ISLE</td>
<td>400</td>
<td>256</td>
<td>144(2)</td>
<td>-</td>
<td>133.60</td>
<td>21.50</td>
</tr>
<tr>
<td>18. MANCHESTER VIGOUR</td>
<td>316</td>
<td>206</td>
<td>110(2)</td>
<td>-</td>
<td>103.10</td>
<td>15.55</td>
</tr>
<tr>
<td>19. EUROLINER</td>
<td>1920</td>
<td>1906</td>
<td>1088</td>
<td>818(3)</td>
<td>224.96</td>
<td>30.00</td>
</tr>
<tr>
<td>20. CALIFORNIA STAR</td>
<td>1107</td>
<td>1107</td>
<td>618</td>
<td>489(4)</td>
<td>-</td>
<td>618</td>
</tr>
<tr>
<td>21. DART AMERICA</td>
<td>1595</td>
<td>1595</td>
<td>1119</td>
<td>476(3)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>22. ELBE MARU</td>
<td>2024</td>
<td>1842</td>
<td>1580</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>23. ATLANTIC MARIELLE</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Equation of the line for 1st tier CTDCKC = 0.0355xLxB - 15.0
Correlation = 0.9678  No. of Data Points = 17.
bunkers are consumed. Erichsen (39) suggests a minimum GM/B value of 0.02 whereas Scott (58) suggests a higher value of 0.04 to 0.05. The three container ship data given by Erichsen (39) and Volker (61) had the following GMT/B values; 2 ships 0.012 and one with 0.019.

The designer can input the required value of GMT as a fraction of the breadth of the ship. Most of the studies in this thesis are carried out with a GMT/B of 0.03. An acceptable minimum GMT is not solely governed by safety requirements against capsizing, since adequate allowance for the operational requirements, such as a constant angle of heel in a lateral wind and the angle of heel when the ship is turning (172), and also reasonable values of GMT while loading and unloading must be made. Taking these factors into consideration a higher initial GMT was stipulated.

13.2.2.2. Statical stability

In spite of the relatively small GMT values and large heeling moments caused by lateral wind pressure, container ships have a wide range of stability on account of their large freeboard. Albert (173) shows that even with a negative GM of 60 cm in Beaufort 12 weather conditions the large freeboard present in a containership will allow the vessel to survive.

Statistical stability is calculated in the subroutine subprogram CROSSC. A set of linear equations developed by Kupras and Majewski (179) are given in the form of diagrams for displacement force lever KN.

The displacement force lever is expressed as a function of the ship's main particulars,

$$\text{KN sin } \Theta = \text{function}(B, T, D, W, C_b)$$

where $W =$ the mean sheer, $(\text{sheer aft} + \text{sheer 'ford})/2$.

On the basis of the diagrams published by Kupras and Majewski (179), Kupras (48) carried out regression analysis and the following relationship between the displacement force
lever and the ship's main particulars was suggested (see Fig. (A)).

$$\text{KN}'_\theta = \text{KN} \sin \theta = \left( A_{11} + A_{12} x + A_{31} \frac{W}{B} + A_{41} \frac{D}{B} + A_{51} \frac{B}{T} \right) x \frac{B}{20} \text{ m.} \quad \text{(Eq. 13.24)}$$

$$\text{KN}'_\theta = 1.025 \left( A_{1} + A_{2} x C_{b} + A_{3} \frac{W}{B} + A \frac{D}{B} + A_{5} \frac{B}{T} \right) x \frac{B}{20} \text{ m.} \quad \text{(Eq. 13.25)}$$

The sets of coefficients $A_1$ to $A_5$ are given in Table 13.7. Once the values of $\text{KN}'_\theta$ are known $GZ$ at various angles of heel are calculated by

$$GZ = \text{KN}_\theta - KG \sin \theta \text{ m.} \quad \text{Eq. (13.26)}$$

Equation (13.25) is valid only for full load draft (design draft), ships with series 60 hull form with parabolic sheer but superstructures are not included.

The following conditions for statical stability were checked in accordance with the Load Line Rules (49).

(a) Area under the $GZ$ curve from $0^\circ$ to $30^\circ$ should be greater than 0.055 metre radians.

(b) Maximum $GZ$ should be greater than 0.20 m. and should occur at an angle more than $30^\circ$.

(c) Area under the curve up to $40^\circ$ should be greater than 0.09 metre radians.

(d) Area under the curve between $30^\circ$ and $40^\circ$ should be greater than 0.03 metre radians.

(e) Initial $\text{GM}_T$ should not be less than 0.15 m.

If any of these constraints are violated the program indicates this by printing out an error message.

13.2.2.3. Influence of draft

As the container ship design draft is less than that permissible by minimum Type-B freeboard, the containers on deck decrease with higher draft for the same initial $\text{GM}_T$ but the average weight of each container increases. The form of the curve, see Fig. 13.8, is similar to the one.
TABLE 13.7. Values of coefficients at various angles.

<table>
<thead>
<tr>
<th>θ in degrees</th>
<th>A₁</th>
<th>A₂</th>
<th>A₃</th>
<th>A₄</th>
<th>A₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.004</td>
<td>-</td>
<td>-</td>
<td>2.5</td>
<td>-0.004</td>
</tr>
<tr>
<td>20</td>
<td>-0.305</td>
<td>-</td>
<td>0.1333</td>
<td>5.0</td>
<td>0.1</td>
</tr>
<tr>
<td>30</td>
<td>-1.641</td>
<td>0.305</td>
<td>0.6467</td>
<td>7.3</td>
<td>0.65</td>
</tr>
<tr>
<td>40</td>
<td>-2.815</td>
<td>-0.2</td>
<td>1.1333</td>
<td>9.25</td>
<td>1.1</td>
</tr>
<tr>
<td>50</td>
<td>-3.0325</td>
<td>-0.3</td>
<td>1.6</td>
<td>10.375</td>
<td>1.23</td>
</tr>
<tr>
<td>60</td>
<td>-2.4045</td>
<td>-0.5</td>
<td>2.0</td>
<td>11.125</td>
<td>1.036</td>
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</table>

<table>
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<tr>
<th>D/B &lt; 0.58</th>
<th>A₁</th>
<th>A₂</th>
<th>A₃</th>
<th>A₄</th>
<th>A₅</th>
</tr>
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<tbody>
<tr>
<td>10</td>
<td>0.671</td>
<td>-</td>
<td>-</td>
<td>1.35</td>
<td>-0.004</td>
</tr>
<tr>
<td>20</td>
<td>0.004</td>
<td>-</td>
<td>0.1333</td>
<td>4.625</td>
<td>0.1</td>
</tr>
<tr>
<td>30</td>
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<td>0.6467</td>
<td>8.25</td>
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</tr>
<tr>
<td>40</td>
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<td>-0.2</td>
<td>1.1333</td>
<td>11.00</td>
<td>1.1</td>
</tr>
<tr>
<td>50</td>
<td>-4.1925</td>
<td>-0.3</td>
<td>1.6</td>
<td>12.375</td>
<td>1.23</td>
</tr>
<tr>
<td>60</td>
<td>-3.492</td>
<td>-0.5</td>
<td>2.0</td>
<td>13.000</td>
<td>1.036</td>
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</table>

<table>
<thead>
<tr>
<th>D/B ≧ 0.62</th>
<th>A₁</th>
<th>A₂</th>
<th>A₃</th>
<th>A₄</th>
<th>A₅</th>
</tr>
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<tbody>
<tr>
<td>10</td>
<td>1.043</td>
<td>-</td>
<td>-</td>
<td>0.75</td>
<td>-0.004</td>
</tr>
<tr>
<td>20</td>
<td>1.043</td>
<td>-</td>
<td>0.1333</td>
<td>2.325</td>
<td>0.1</td>
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<tr>
<td>30</td>
<td>-0.301</td>
<td>-0.1</td>
<td>0.6467</td>
<td>5.2</td>
<td>0.65</td>
</tr>
<tr>
<td>40</td>
<td>-2.28</td>
<td>-0.2</td>
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<td>1.1</td>
</tr>
<tr>
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<td>-2.5525</td>
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<td>1.23</td>
</tr>
<tr>
<td>60</td>
<td>-2.407</td>
<td>-0.5</td>
<td>2.0</td>
<td>11.125</td>
<td>1.036</td>
</tr>
</tbody>
</table>

Base line

\[ KN_\theta = KN_\theta \sin \theta \]

Fig. A 338
Fig. 13.8. Parametric variation in draft, initial $GM_T$ and ballast.

- $GM_T = 0.45$ m
- $GM_T = 0.30$ m
- $GM_T = 0.15$ m

GM_T = 0.15 m and 2 1/2% of displacement as ballast

Total container capacity in Teu
shown in Fig. 13.2. Area under the GZ curve also increases as the draft decreases, because the freeboard increases thereby improving the area under the GZ curve (Fig. 13.9). Therefore by decreasing the draft a higher number of deck containers can be loaded but with lower average weight of each container.

13.2.2.4. Influence of GMT

Initial GMT was increased to 0.30 m. and 0.45 m. from 0.15 m. The effect is shown in Fig. 13.8. As the initial GMT is increased the container capacity decreases and the decrease with GMT of 0.15 m. to 0.30 m. and from 0.30 m. to 0.45 m. is of the same magnitude. Moreover, this decrease is more or less constant with variation in draft. However the average weight of each container at corresponding draft increases with increase in GMT.

13.2.2.5. Influence of adding ballast

As mentioned earlier, one way of improving the stability of the ship was to increase the metacentric height by increasing the beam. However, as the container ship becomes larger, the beam is restricted, for example, ships transiting through the Panama Canal have limiting beam of 32.26 m. Since transverse metacentre is largely governed by the hull geometry and the centre of gravity is a function of the disposition of the weights, the only way to improve the transverse metacentric height GMT is to lower the centre of gravity of the ship. This can be achieved by adding ballast to the double bottom spaces. Erichsen (39) suggests a ballast weight of 2½ % of displacement for container ships. As shown in Fig. 13.8, with ballast a container-ship can increase considerably its container carrying capacity. However the average weight of each container is less at corresponding draft compared to a ship without ballast.
Fig. 13.9. Effect of freeboard on the area under the GZ curve.

Angle of heel in degrees

GZ in m.

11.0 m. draft

12.0 m. draft

13.0 m. draft

$GM_T$, $T = 11.0$

$GM_T$, $T = 12.0$

$GM_T$, $T = 13.0$
Seakeeping is an important consideration in the preliminary design stage. Swift (55) had studied the effect of seakeeping on container ship design, and had come to the conclusion that deck wetness and slamming constraints were important. Journee (180) considers the speed reduction due to added resistance caused by wind and waves as well as voluntary speed reductions by the Captain due to severe motions. Beukelman & Huijser (181) have used a program 'TRIAL' to determine the seakeeping qualities in the head waves of systematically varied ship hull forms of Todd-60 series. They found (181) that the following parameters in descending order of importance had major influence on the ship's seakeeping qualities.

(a) Length. (b) Speed. (c) Forebody section shape. (d) Block coefficient. (e) Position of centre of buoyancy along the ship's length. (f) Radius of gyration. These computer models incorporating seakeeping criteria are quite extensive and their use requires detailed input data of the sea states and the probability of their occurrence as well as hull form particulars, intended routes and ship's heading. The sea state information is readily available but to input to the program requires considerable effort.

Since only the principal dimensions are known at the preliminary design stage and large numbers of alternative designs are possible, use of such programs are limited.

For the preliminary design stage Aertssen (182) gives a simpler equation for predicting the percentage loss in speed with special emphasis on the relation between wind and waves. The percentage loss in speed is expressed as

\[ \frac{100}{V} \Delta V = \frac{m}{L_{BP}} + n \ \text{percent.} \quad \text{Eq. (13.27)} \]

where \( m \) and \( n \) are coefficients, values of which depend on the heading and the severity of the sea. Though this equation does not require knowledge of the hull form it assumes
that the frequency of occurrence of the various sea states are known. And the results are reliable only if the frequency of the various sea states are known (182), which may not be possible to predict at the preliminary design stage.

Babbage (183) proposes another equation which can be used for the preliminary design of ships for which no voyage data are available. The form of the speed power curve is usually known at the preliminary design stage. A coefficient $N$ which completely describes the shape of this speed power curve and expressed as $N = \frac{dP}{dV} \cdot \frac{V}{F}$ is used to predict the loss in speed.

The speed loss ($\Delta V$) is given by

$$\Delta V = N \times L_{BP}^{0.63} \times 0.03 \text{ knots} \quad \text{Eq. (13.28)}$$

The above equation was derived by regression analysis on a limited set of data (8 ships) and therefore can be regarded as the best value only for this set of data. Unfortunately, there does not seem to be any simple approach which considers ship motions and their coupling using only the principal dimensions. Therefore as far as seakeeping was concerned it was understood that any coupling between rolling, pitching or heaving would give rise to maximum motions. And for this it was essential that at least roll, pitch and heave characteristics should be examined. Lamb (105), Baxter (184) and Kupras & de Zwaan (185) have used the following expressions for calculating the natural periods of Roll, Pitch and Heave.

$$T_{\text{Roll}} = 2.0069 \times B \times \left( (0.13 \times (C_b \times (C_b + 0.2) - 1.1 \times (C_b + 0.2)(2.2 - \frac{D}{T}) \times (1 - C_b) + (D/B)^2) \right) / GMT \right)^{1/2} \text{ secs.} \quad \text{Eq. (13.29)}$$

$$T_{\text{Pitch}} = \left( \frac{1.775}{C_w} \right) \times (T \times C_b \times (0.6 + 0.36 \times \left( \frac{B}{T} \right)))^{1/2} \text{ secs.} \quad \text{Eq. (13.30)}$$

$$T_{\text{Heave}} = 2.0069 \left( (T \times C_b \times (0.333 \times \left( \frac{B}{T} \right) + 1.2)) / C_w \right)^{1/2} \text{ secs.} \quad \text{Eq. (13.31)}$$
In order to prevent such extreme coupled motions, the ratios $T_{\text{roll}}/T_{\text{pitch}}$ and $T_{\text{roll}}/T_{\text{heave}}$ should never be equal to 2 and the ratio $T_{\text{pitch}}/T_{\text{heave}}$ should not be equal to 1 (105, 184, 185) was assumed as a seakeeping criteria in the program. The calculation is carried out in the subroutine subprogram SEAKEP.

13.4. PARAMETRIC METHOD (COMPUTER MODEL I)

Early approaches to ship design were based on examining a few hypothetical ships over the range of interest, the calculation being done manually and the results plotted graphically to arrive at the optimum design, e.g. Benford 1957 (186) for tankers, Benford 1958 (62) for ocean ore carriers, Benford et al. 1962 (187) for iron ore ships, Mack-Forlist and Hettena 1966(188) for bulk carriers and Krappinger 1967 (154) for Great Lakes ore-carrier economics.

With the advent of computers, came the ability to study a greater number of designs than was possible by earlier manual methods. One of the first replications of the manual design techniques on computers was done by Murphy, Sabat and Taylor 1965 (189). Earlier approaches, where economic study was limited to examining a few possible designs the computer aided approach (189) extended the number of feasible designs to 1024 a factor of 100. A more interesting advancement was not the repetition of manual tasks on the computer but that computers allowed one to do away with approximating equations due to the use of subroutines which gave better results (190), with more complex relationships.

The usual method for generating the large number of designs is by systematic variation of the independent variables by means of group of nested loops (191) with FORTRAN, 'DO' statements and searching for possible designs in a predefined feasible space. The constraints are solved either as equality constraints or as inequality constraints. Solving of equality constraints would usually require a larger number of iterations,
therefore these are replaced by two inequality constraints. Such procedures have been successfully applied to design of dry cargo ships by Murphy, Sabat and Taylor, 1965; tankers, bulk carriers and combination carriers by Kuniyasu 1968 (192); bulk carriers by Gilfillan 1969 (193); oil tankers, bulk carriers, cargo liners and container ships by Cameron 1970 (86); warships by Eames and Drummond 1977 (194); general cargo by Validakis 1978 (120) and to tankers both crude and products carrier by the British Ship Research Association (195). Equal level contours for constraints and objective function is found by graphical or analytical interpolation in all these methods and displayed graphically to show the region near the optima.

In spite of the introduction of optimization techniques which allows one to automate the search procedure the parametric method has not lost its attraction. This is mainly because of the flat laxity in the region of the optimum, where large numbers of designs with required freight rate (RFR) very close to the minimum RFR are possible. At the preliminary design stage a designer is more interested in examining the region around the optimum rather than only the optimum. This is mainly because of the large number of approximating equations used in the preliminary design stage. Therefore this was the first step in building the total suite of programs containing four independent computer algorithms for preliminary design of container ships. Out of these four, two are used in the deterministic phase of the design and two in the probabilistic phase of the design. In the deterministic phase, one of these computer models, henceforth designated as MODEL I uses parametric variation of the independent variables to generate large numbers of feasible designs. The designer then scans the various designs manually to locate the optimum design based on an economic criterion, here chosen as Required Freight Rate. The second computer model designated as MODEL II utilises the optimization technique to arrive at the optimum design and is described.
more fully in Section 13.5. The other two computer models used in the probabilistic phase are designated as MODEL III and MODEL IV and are described more fully in Chapter 15.

MODEL I forms the basic building brick of the later computer models. The basic structure of MODEL I is shown in Fig. 13.10. The main program logic is shown in Appendix 2. It involves parametric variation of length, breadth, depth, draft and block coefficient. The method basically involves generating large numbers of designs from the possible combinations of L, B, T, D and C_b. The user can specify the following values of input which can expand or restrict the generation of large numbers of designs or enable a designer only to generate designs in the region of the optimum
(a) final and starting values of the block coefficient, and the step size.
(b) The number of rows and tiers.
(c) Maximum and minimum values of L/D, B/T, L/B ratios.
(d) The step sizes were for L =1.0 m, B = 0.5 m, D = 0.4 m. and T = 0.5 m.

These could be increased or decreased, but because of the simultaneous equality constraints of container capacity, initial stability criteria GM_T and weight of each container, the step width of draft had always to be kept around 0.5 m.

The explicit constraints which were considered in the program are,
(a) Circular (C) for certain values of C_b and V/\sqrt{L} are not available, particularly for higher values of C_b and V/\sqrt{L}.
(b) Check that field efficiency is within the Bp-5 chart.
(c) The blade area ratio lies between 0.45 and 1.05.
(d) The calculated values of the container carrying capacity is within the limits of the required container capacity. In the program a tolerance limit of ± 1% was kept.
(e) The program generates design of ships with average weight/container from 8 tons to 20 tons. These values can be increased or decreased to narrow down the limits, to the specified weight of each container.
Fig. 13.10. Program structure deterministic phase with parametric variation of independent variables. (Computer Model I).

Main program
parametric
variation in
LBP,B,T,D,CB+
Read + Write
statements
(24605)

Subroutine
condcf
(2018)

Subroutine
bidgco
(786)

Subroutine
hancos
(558)

Subroutine
runcos
(824)

Subroutine
fuelco
(476)

Subroutine
voytime
(558)

Subroutine
payload
(342)

Subroutine
seekep
(1364)

Subroutine
design
(1084)

Subroutine
frebrd
(716)

Subroutine
capchr
(660)

Subroutine
prewor
(164)

Subroutine
efechp
(3934)

Subroutine
lagint
(212)

Subroutine
anpval
(2702)

Subroutine
econom
(8686)

Subroutine
stabil
(2644)

Subroutine
crosec
(2116)

Subroutine
condcf
(2018)

Subroutine
bidgco
(786)

Subroutine
hancos
(558)

Subroutine
runcos
(824)

Subroutine
fuelco
(476)

Subroutine
voytime
(558)

Function
eovsle1
(168)

Function
eovsle2
(134)

Function
denamb
(206)

Function
efnemb
(266)

Function
prsnmb
(266)

Subroutine
denspwr
(2012)

Subroutine
cavpit
(530)

Subroutine
polone
(156)

Note: Figures within brackets indicate the size of the algorithm (Total 132K).
(f) Messages are printed for designs which do not meet the seakeeping criteria and the statical stability criteria. Implicit constraints which are satisfied by restricting the main particulars of the ship within those limits are

- Minimum and maximum values of block coefficient, denoted by $SCB = 0.48$ and $FCB = 0.72$.
- Minimum and maximum values of $L/D$ ratio, between 10 and 14.5.
- Minimum and maximum values of $B/T$ ratio, between 2.25 and 3.75.
- Minimum and maximum values of $L/B$ ratio, between 6.0 and 9.0.
- Minimum and maximum values of $V/L$ ratio, between 0.40 and 1.5.

The various subroutine subprograms, function subprograms and the main program attributes, and sizes are also shown in Fig. 13.10. There were two types of options for printing the input and the output. One was summary input and output used primarily for printing all the feasible designs and the other is an extended input and output option used only for generating designs in the region of the optimum. An extended input and output printout is shown in Fig. 13.11.

For generating about 2000 designs, for three values of block coefficient required 1500 secs. of computer time.

13.5. OPTIMISATION TECHNIQUES (COMPUTER MODEL II)

The parametric variation of principal dimensions to generate large number of designs is time consuming and expensive to run. Therefore an effort was made to automate the search procedure. Parsons (1) gives an excellent review of the existing techniques and their application to ship design in the past. Before the algorithm given by Parsons was adopted, various other algorithms were studied. These included the algorithm given by Box (196) and FORTRAN computer codes given by Kuester and Mize (197); Numerical
Algorithm Group NAG library routines (198), E04UAF; OPRQP (OPXRQP) in conjunction with OPND3 developed by Numerical Optimisation Centre of the Hatfield Polytechnic (199), flexible tolerance method (200) based on Nelder and Mead's Simplex Method (3) for which computer codes are given by Himmelblau, and Direct Search technique of Hookes and Jeeves for which computer codes are given by Kupras (201).

All these computer codes are developed for solving non-linear objective functions with non-linear as well as linear equality and inequality constraints. However except for Box's Algorithm all other computer codes could not be implemented on the ICL 2976 computer with VME-B operating system because of various reasons given below:

1. NAG library routines can only be used in double precision. This increased the required memory space to twice the size for each of the variables. Though the routine does not require the evaluation of derivatives, it is intended only for functions and constraints which have continuous first and second derivatives.

2. Similarly OPRQP (OPXRQP) and OPND3 also required continuity of first and second derivatives which could not be ensured, because of the large number of approximate equations used in the program needed to be tested. Moreover the source program was written for IBM machines which meant that lots of statements needed modification.

3. FLEXIPLEX or flexible tolerance method failed to work on ICL 2976 because of either certain errors in the source program or printing errors.

4. Better point algorithm by Kupras had computer codes only in ALGOL and therefore not accepted.

Two computer codes were therefore available, one given by Kuester and Mize (197) and the other by Parsons (1), both of which were implemented successfully on the ICL 2976 at Glasgow University Computing Centre. The computer code given by Parsons was adopted because of the following reasons.
Box's algorithm is a Random Search Technique, which requires a library subroutine for generation of random numbers. Since generation of random numbers is machine dependent, implementation from one computer to another will be difficult. For ICL 2976, NAG library routine G05CAF was used to generate pseudo-random real numbers between 0 to 1 taken from a uniform distribution.

The computer codes given by Parsons gives the user the option to use either Hooke and Jeeves (2) direct search or Nelder and Mead (3) simplex search with external penalty technique. Therefore if one of the optimization methods fails the other could be used.

The program structure employing Parsons' computer codes together with subroutines FUNCTN and CONSTR developed specifically for container ships is shown in Fig. 13.12. To use the computer codes given by Parsons the user need only supply subroutine FUNCTN and CONSTR. Except one small error in the program code i.e. the statement number 40 in subroutine Hooke is redundant, the rest of the program did not give any compilation or run time errors. The use and various functions of the subroutines are well covered by Parsons (1) and are not repeated here.

The search procedure to reach an optimum design was cut down from 1500 secs. for three block coefficient values in step sizes of 0.01 in Computer MODEL I to 200 ~ 400 secs. of computer time in Computer MODEL II. This however does not include the different starting points that must be attempted before a global optimum is reached. The parametric search procedure could only be run on a batch mode, with only limited amounts of interactive computing in the region of optimum. The optimisation technique allowed one to see the progress of the search procedure in an interactive mode. With experience, when a feel for the various possible starting values was developed, interactive computing took less than 5 minutes to arrive at the optimum. Obviously the optimisation method should be preferred once the user has
Fig. 13.12. Program structure deterministic phase with application of optimisation techniques (Computer Model II)

Main program
read in data
initial values of
independent
variables +
other parameters
(23607)

OptOpt > 0
2
Optopt = 1
or 2
1

Subroutine
constr
(3214)

Subroutine
simplex
(5364)

Subroutine
functn
(3290)

Subroutine
constr
(3214)

Subroutine
Hooke
(2422)

Subroutine
constr
(3214)

Subroutine
Jeeves
(653)

Subroutine
ctrl
(446)

Subroutine
functn
(3290)

Subroutine
constr
(3214)

Subroutine
extpen
(516)

Function evaluation only

Nelder and Mead
Method

Hooke & Jeeves
Method

Note: Figures within brackets indicate the size of the algorithm. (Total 158K).
acquainted himself with the working procedure.

Optimisation techniques are criticised because it is often misunderstood as a black-box type of approach or the notion that only one optimum design is output. Print options are included in the program, which allows the user to follow the procedure quite easily and to observe which constraints are not being fully met. To observe designs in the region of the optimum the user can then use the parametric method using computer MODEL I.
CHAPTER 14

PARAMETRIC STUDY AND SENSITIVITY ANALYSIS

14.0 INTRODUCTION

14.1 SYSTEMATIC VARIATION OF SHIP SIZE AND SPEED

14.2 OPTIMUM SPEED

14.2.1. EFFECT OF HIGHER FUEL PRICES

14.2.2. EFFECT OF HIGHER CREW COSTS

14.2.3. EFFECT OF HIGHER DISCOUNT RATE

14.2.4. EFFECT OF HIGHER FIRST COST

14.3. SENSITIVITY ANALYSIS

14.3.1. MERIT RANKING

14.3.2. VARIATION IN NUMBER OF PORTS, SHIP SIZE AND SPEED

14.3.3. VARIATION IN DELAYS, SHIP SIZE AND SPEED

14.3.4. VARIATION IN DISCOUNT RATE, INCOME TAX AND SHIP'S LIFE
14.0. Introduction

In the previous chapters the various computer subprograms were described together with the methods employed, assumptions made regarding some of the variables and their testing and validation. Section 13.4 gave the basic linking of the subprograms for Computer Model I while Section 13.5 gave this for Computer Model II. These two computer models are used in the deterministic phase of the design.

Although individual subprograms may give reasonable results when used alone, tests are needed to ensure that they give reasonable results when linked together and these tests involve examining situations whose outcome is well established; such as the reduction of optimum speed with increase in fuel prices.

Sensitivity analysis is useful to indicate numerically, the gains resulting from improvement of particular variables. In particular cost and weight estimation may be improved with effort and the extent of this effort must be traded against the expected gain in the measure of merit.

This chapter shows that computer Models I and II can be used for ships of container capacity of 500 to 2500 Teu. Only nineteen container ships of carrying capacity above 2500 Teu are in operation (Table 4.8) today. Hence ships of container capacity above 2500 Teu were not included in the study, although the computer Models I and II can be used for ships of block coefficient 0.50 to 0.70 and speed length ratio, $V/\sqrt{L}$ of 0.40 to 1.5, which covers the range of speeds and powering requirements of most container ships.

Systematic variation of ship size and speed was carried out to find optimum values of these parameters. A sensitivity analysis was performed which illustrated the particular importance of steel weight estimation for container ships which are usually stability limited designs. Considerations such as certain number of calls per week to maintain a scheduled service, cargo inventory costs and cargo availability have not been included.
14.1. Systematic variation of ship size and speed

Systematic variation of ship size and speed were carried out for the following assumptions for a North Atlantic trade route of 6770 n. miles round trip.

Table A

<table>
<thead>
<tr>
<th>Case</th>
<th>Assumption A</th>
<th>Assumption B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Dimensions of container</td>
<td>20' x 8' x 8'</td>
<td>20' x 8' x 8'6&quot;</td>
</tr>
<tr>
<td>Weight of empty container</td>
<td>2 tons</td>
<td>2.2 tons</td>
</tr>
<tr>
<td>Gross weight of each container</td>
<td>14 t</td>
<td>14 t</td>
</tr>
<tr>
<td>Specific fuel consumption</td>
<td>162.0 gms/bhp.hr</td>
<td>135 gms/bhp hr.</td>
</tr>
<tr>
<td>Discount Rate</td>
<td>15%</td>
<td>7%</td>
</tr>
<tr>
<td>Loan terms for ship acquisition</td>
<td>12%</td>
<td>0% interest</td>
</tr>
<tr>
<td>Tax rate</td>
<td>52%</td>
<td>0%</td>
</tr>
</tbody>
</table>

For case study 1 ship size was varied from a container capacity of 500 Teu to 2500 Teu in steps of 250 Teu. Ship speed was varied from 15 knots to 30 knots in steps of 1 knot. For case study 2 ship size was varied from a container capacity of 1000 Teu to 2250 Teu in steps of 250 Teu. Ship speed was varied from 15 knots to 30 knots in steps of 1 knot. For case studies 3 and 4 ship size was varied from a container capacity of 1000 Teu to 2250 Teu in steps of 250 Teu. Ship speed was varied from 15 knots to 27 knots in steps of 1 knot. Further for case studies 2, 3 and 4 ballast of 5% of displacement and ballast of 10% of displacement were also considered.
The program only considers ballast in the double bottom and does not confirm that adequate tank space is available for ballast as well as bunkers but some spot checks indicate that there is ample provision for 5% ballast. A need for 10% ballast in all designs might impose a constraint on double bottom height although a program to incorporate ballast considerations would need to involve wing tanks.

The optimum dimensions for each ship was calculated at a particular speed. The principal dimensions of the ship together with the number of rows and tiers of container were input: Computer Model II was used in all cases to produce the results and the Nelder and Mead Search procedure option was preferred. The global solution was found by changing the initial starting point of L, B, T, D and $C_b$. The optimum hold arrangement was found by varying the configuration of rows and tiers, but this variation was limited to two possible configurations. There were four tiers of deck containers included in the input number of container tiers. The initial number of tiers in the hold is the total number of tiers less four. The number of deck containers are then varied in an iterative manner to meet the stability requirements.

**Table B**

<table>
<thead>
<tr>
<th>Trial</th>
<th>Dimensions in metres</th>
<th>£/tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L</td>
<td>B</td>
</tr>
<tr>
<td>1</td>
<td>210.25</td>
<td>29.50</td>
</tr>
<tr>
<td></td>
<td>218.71</td>
<td>28.63</td>
</tr>
<tr>
<td></td>
<td>225.56</td>
<td>28.63</td>
</tr>
<tr>
<td>2</td>
<td>236.99</td>
<td>28.65</td>
</tr>
</tbody>
</table>

Starting values, user

Final values, computer

Starting values, user

Final values computer
The above Table B shows the input values to achieve the optimum for a ship of container capacity 1250 Teu and speed of 29 knots. In this case the number of hold tiers will be 8 although 7 hold tiers is considered. The ship with 8 tiers in hold gives a lower value RFR. The ship with 7 hold tiers is eliminated at this speed and the global optimum found by initiating the search from three to four different values of L, B, T, D and C_b. The step sizes found adequate for the search procedure using Nelder and Mead's method were L = 5.0 m, B = 0.5 m, T = 0.5 m, D = 0.5 m and C_b = 0.3 and convergence limits were

L = 0.01, B = 0.01, T = 0.01, D = 0.01 and C_b = 0.001.

Nelder and Mead's simplex method was used throughout because the convergence to the optimum was faster compared to Hooke and Jeeves Direct Search method (see Section 13.5 for user option).

The following table shows the optimum hold configuration for various ship sizes over a range of speeds.

Table C

<table>
<thead>
<tr>
<th>Container Capacity</th>
<th>500</th>
<th>750</th>
<th>1000</th>
<th>1250</th>
<th>1500</th>
<th>1750</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rows</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Hld. Tiers</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Container capacity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>2250</td>
<td>2500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rows</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hld. Tiers</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The value of RFR for each ship size was plotted against speed as shown in Fig. 14.1 to Fig. 14.9. An important factor in the discontinuity in the curve is the jump from single to twin screw installations when the installed power is about 50000 hp.
Fig. I4.2 Speed variation series for 750 Teu container ship
Fig. I4.3 Speed variation series for 1000 Teu container ship

Case 3
WEC=40 T. 8'6" HIGH CONTAINER

Case 1
WEC=4 T. 8' HIGH

Case 4
WEC=7 T. 8'6" HIGH

Case 2
WEC=4 T. 8'6" HIGH

10% water ballast
5% water ballast
0% water ballast

Ship speed in Knots

Required Freight Rate £/tonne

WEC=7 tonnes
Fig. I4.4  Speed variation series for 1250 Teu container ship

Case 3
WEC=105 T. 8-6' HIGH CONTAINER

Case 1
WEC=44 T. 8' HIGH

Case 4
WEC=7 T. 8-6' HIGH

Case 2
WEC=14 T. 8-6' HIGH

10% water ballast
5% water ballast
0% water ballast
Fig. 14.5 Speed variation series for 1500 Teu container ship

Case 4
WEC = 7 T, 8'-6" HIGH CONTAINER

Case 3
WEC = 10.5 T, 8'-6" HIGH

Case 1
WEC = 14 T, 8' HIGH

Case 5
Zero sets of containers and cost of containers = 0
WEC = 10.5 T, 8'-6" HIGH

Case 2
WEC = 14 T, 8'-6" HIGH

10% water ballast
5% water ballast
0% water ballast
Fig. 14.6 Speed variation series for 1750 TEU container ship

Case 4
WEC=7T, 8'-6" HIGH CONTAINER

Case 1
WEC=14T, 8'-0" HIGH

Case 3
WEC=10.5T, 8'-6" HIGH

Case 2
WEC=14T, 8'-6" HIGH

10% water ballast
5% water ballast
0% water ballast

Required Freight Rate £/tonne

WEC=7 tonnes
WEC=10.5 tonnes

Ship speed in Knots

15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Fig. 11.7 Speed variation series for 2000 Teu container ship

Case 3
WEC=105 T. 8'6" HIGH CONTAINER

Case 1
WEC=14 T. 8' HIGH

Case 4
WEC=7 T. 8'6" HIGH

Case 2
WEC=14 T. 8'6" HIGH

10% water ballast
5% water ballast
0% water ballast

Shipment speed in Knots
Fig. 14.8 Speed variation series for 2250 TEU container ship
Fig.14.9 Speed variation series for 2500 Teu container ship
Case 1

The optimum ship size is in the region of 1500 Teu to 1750 Teu and the optimum speed is between 15 to 20 knots as shown in Fig. 14.1 to Fig. 14.9.

The rate of increase outwith this region favours ships from 1500 Teu to 1750 Teu rather than 1500 to 1250 Teu. The value of RFR does not change much with speed over a reasonable range for ships above 1250 Teu. No doubt the reduction in Froude number is important.

For speeds of 18, 21, 24 and 27 knots the RFR was plotted against ship size as shown in Fig. 14.10 to Fig. 14.13. The optimum size occurs at 1500 Teu for speeds of 18 and 21 knots (Fig. 14.10 and Fig. 14.11). The flat laxity of ship size with RFR is apparent in Fig. 14.12 and Fig. 14.13 at the higher speeds of 24 and 27 knots, but at these higher speeds little is gained by increasing the ship size beyond 2000 Teu.

The range of sizes that are within a small defined departure from the optimum can be found. Increases of 2½ % and 5% in RFR were studied as shown in Fig. 14.10 to Fig. 14.13. The size variation for various speeds within these ranges if minimum RFR are shown below.

<table>
<thead>
<tr>
<th>Speed in knots</th>
<th>2½% RFR variation</th>
<th>5% RFR variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>1000 - 1970</td>
<td>850 - 2250</td>
</tr>
<tr>
<td>21</td>
<td>990 - 2030</td>
<td>830 - 2440</td>
</tr>
<tr>
<td>24</td>
<td>1210 - 2250</td>
<td>1030 - 2530</td>
</tr>
<tr>
<td>27</td>
<td>1040 and above</td>
<td>870 and above</td>
</tr>
</tbody>
</table>

At 2½ % variation in RFR the size variation is about 1000 Teu and at 5% variation in RFR the size variation is about 1500 Teu at all speeds.
Fig. I4.10 Size variation series 18 Knots

Acceptable ship size for 2½% variation in RFR min.
Acceptable ship size for 5% variation in RFR min.
Fig. I4.12  Size variation series 24 Knots

Required Freight Rate /tongue

Case I

Acceptable ship size range for 5% variation in \( RFR_{\text{min}} \).  
Acceptable ship size range for 2½% variation in \( RFR_{\text{min}} \).

Container capacity in Teu

1030 1210
A main influence on the small change in RFR with size is the container handling cost. Container handling cost is directly proportional to the number of containers and has no economy of scale. In the ships considered this cost is about 50% of the operating cost. Costs that do have economy of scale such as fuel costs and crew costs etc. account for about 40% of the total operating costs. The remaining costs such as insurance tend to be related to the first cost. Consequently as the number of Teus increase any variation in RFR caused by size alone is modest for this length of trade route.

Fig. 14.10 to Fig. 14.13 indicate that for a certain speed there is an optimum number of Teu giving the lowest value of RFR. For smaller number of Teus the vessel is too expensive at sea mainly caused by high fuel costs in relation to payload and for larger values the vessel is too expensive in port mainly caused by inability to speed up the turnaround time. The influence of increase of speed is to flatten the curve to give a wider range of Teus without significant change in RFR and to increase the optimum number of Teus.

Cases 2, 3 and 4

Fig. 14.3 to Fig. 14.8 illustrates the effect of ballast on RFR for ships of container capacity 1000 to 2250 Teu at various speeds and average weight of each container of 14, 10.5 and 7 tonnes.

A careful study was made of the figures obtained when 5% and 10% ballast was incorporated but it is not possible to come to precise conclusions. Naturally when using a program where RFR is based on the mass of cargo carried the best values of RFR are without ballast. In most cases the RFR worsens as the ballast is increased from 5% to 10% of displacement. However in a number of cases 10% ballast is shown to be better than 5% ballast. This trend must be viewed in conjunction with the precision of the program and its optimising routines compared with the percentage change
of RFR in moving from zero to 10% ballast situations.

In broad terms there is no exact explanation of this reversal of trend but when it occurs the length of the design chosen is less for 10% ballast than for 5% ballast condition and this is deemed to be the main reason for the fluctuation of RFR.

Case 5

Under assumption B, optimum ship dimensions were found for the weight of each container 10.5 tonnes and also assuming that there were zero sets of containers and the cost of maintaining and operating these containers was excluded. Containers are usually leased and are operated for a fleet of vessels and therefore not included in the acquisition cost of the ship. However it has been assumed in this thesis that containers are owned by the shipping company.

Fig. 14.5 shows the Required Freight Rate at various speeds for a 1500 Teu containership, excluding the cost associated with a finite set of containers. This Required Freight Rate is designated as $RFR_1$ and the Required Freight Rate including cost of acquisition and operating 2.5 sets of containers as $RFR_2$.

The ratio $RFR_2/RFR_1$ decreases progressively from a value of 1.40 at lower speeds of 15 knots to 1.22 at higher speeds of 27 knots and this decrease is almost linear.

14.2. Optimum Speed

The flat laxity of the RFR curves in the region of the optimum speed, about 17 knots, indicates that there must be little resistance to the influence of competitive pressures to raise the speed and actual speeds of containerships reflect this. Furthermore inclusion of inventory costs will raise the optimum speed. When freight rates are fixed, speed may be regarded as an extension to quality of service and thus higher speeds may bring improved load factors.
For a cost based criterion such as RFR the optimal speed obtained is the speed for minimum average costs and hence the cheapest speed, and this speed ignores the demand aspect of the problem of choice of speed.

14.2.1. Effect of higher fuel prices

A ship of container capacity 1500 Teu was chosen to determine the effect of fuel price changes on the optimum speed of the ship.

The price of fuel oil, diesel oil and lubricating oil was increased by 25% and by 50% and was reduced by 50%, although an improbable occurrence.

Fig. 14.14 shows the change in RFR with respect to speed when the speed was varied from 15 knots to 24 knots in steps of 3 knots. The optimum speed of 17.15 knots falls to 16.60 knots for a fuel price increase of 25% and to 16.05 knots for a fuel price increase of 50% and increases to 18.55 knots for a reduction of fuel price of 50%.

If the economic speeds including inventory costs were higher, then the absolute drop in speed would be accordingly greater and it might be that the relative drop in speed would also be greater. The route would also affect this result and this study has taken a short route; but the results show that higher fuel prices decrease the optimum speed.

14.2.2. Effect of higher crew costs

The crew costs were escalated at 5% per annum and 10% per annum relative to other operating costs to consider the effect of relatively higher crew costs on optimum speed. The effect is shown in Fig. 14.15 but is not significant for the range of crew costs considered.

14.2.3. Effect of higher discount rate

The discount rate at 15% was increased to 17½ % and 20% and decreased to 12½ % and to 10% and the effect of this is shown in Fig. 14.16. The effect on optimal speed is small.
Fig. 14.14. Effect of higher fuel prices on the optimal speed
(Assumption A)
Fig. 14.15  Effect of increase of crew costs on optimal speed
(Relative escalation of crew costs per annum)
(Assumption A)
Fig. 14.16. Effect of higher discount rate on optimal speed (Assumption A)
Fig. 14.17 Effect of higher Shipbuilding cost on optimal speed

- 17.0 Knots
  +50%
- 17.10 Knots
  +25%
- 17.15 Knots
  Basis
- 17.35 Knots
  -50%
14.2.4. Effect of higher first cost

The first cost of the ship (excluding the containers) was increased by 25% and 50% and decreased by 50%. The effect on the optimal speed is shown in Fig. 14.17 and it is small.

14.3. Sensitivity Analysis

In the earlier sections it was shown how computer Model I or computer Model II could be used to generate an optimum design. Computer model II is preferred to computer model I to carry out such studies since it was found to be more economic in terms of computer costs and time. Once the optimum design has been selected a sensitivity analysis is carried out using either computer model I or computer model II.

14.3.1. Merit Ranking

Sensitivity analysis involves making incremental changes to some main items. The main items are those which are usually known to have major influence on the Required Freight Rate or items which cannot be estimated accurately at the preliminary design stage because of their inherent variability over the life of the vessel.

Nineteen major items as listed in Table 14.1, Table 14.2 and Table 14.3 were identified as items for carrying out such sensitivity analysis. A 10% improvement in each of these items was assumed and the life of the ship and the containers was increased by four years. The influence of these items was measured in terms of percentage change in RFR from the basic RFR by changing one item at a time.

The computer Model II was used to carry out sensitivity analysis on ships of container capacity 1500 Teu and a speed of 21 knots for three different weights.

Table 14.1 gives the merit ranking for a containership with average weight of each container 14 tonnes. Similarly
Table 14.1. Sensitivity Analysis with 10% improvement (Model II). Weight of each container $= 14$ tonnes.

<table>
<thead>
<tr>
<th>No.</th>
<th>Items</th>
<th>Units</th>
<th>Initial Values</th>
<th>Final values</th>
<th>Computer Symbol</th>
<th>RFR £/tonne</th>
<th>% Diff. from Basis RFR</th>
<th>Merit Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basis ship</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>28.867</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Load Factor</td>
<td>%</td>
<td>0.85</td>
<td>0.935</td>
<td>ALFO</td>
<td>27.778</td>
<td>3.772</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Round Voyage distance</td>
<td>n.miles</td>
<td>6766</td>
<td>6090</td>
<td>DIST</td>
<td>27.648</td>
<td>4.223</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Container handling cost</td>
<td>£/container move</td>
<td>50</td>
<td>45</td>
<td>CHANDL</td>
<td>28.019</td>
<td>2.938</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>Ship's First Cost</td>
<td>£ x 10^6</td>
<td>24.38</td>
<td>21.94</td>
<td>CAPCOS</td>
<td>28.307</td>
<td>1.939</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>Port time per round voyage</td>
<td>days</td>
<td>13.23</td>
<td>11.91</td>
<td>DIP</td>
<td>27.924</td>
<td>3.267</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>Ship's Life</td>
<td>years</td>
<td>20</td>
<td>24</td>
<td>LIFES</td>
<td>28.483</td>
<td>1.330</td>
<td>13</td>
</tr>
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<td>Average Crew Wages</td>
<td>£/annum</td>
<td>5300</td>
<td>4700</td>
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<td>28.731</td>
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<td>7560</td>
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Table 14.1 (Contd.)

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<th>Computer Symbol</th>
<th>RFR £/tonne</th>
<th>% Diff. from Basis RFR</th>
<th>Merit Ranking</th>
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<td>gms/bhp.hr</td>
<td>135</td>
<td>121.5</td>
<td>Section 8.2.3 and sec.</td>
<td>28.254</td>
<td>2.123</td>
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<td>£/hr.</td>
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<td>2.16</td>
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<td>Operating Costs</td>
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<td>£/tonne</td>
<td>214</td>
<td>192.6</td>
<td>STLCOS</td>
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<td>18</td>
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<td>COSCNT</td>
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<td>years</td>
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Basis ship. Container Capacity 1500 Teu, speed = 21 knots, North Atlantic Route, 2 ports of call, average weight of each container = 14 tonnes, without ballast.

\[ L_{BP} = 221.472, \quad B = 29.877, \quad T = 9.291 \quad D = 19.742, \quad C_b = 0.631. \]

Life of ship and life of container increased by 4 years, steel weight estimation method 4 option used (Section 6.1). Dimensions in metres.
Table 14.2 and Table 14.3 gives the merit ranking for containerships with average gross weight of each container 10.5 tonnes and 7 tonnes respectively.

In all these cases assumption B as given in Table A was applicable.

Table 14.4 summarises the results of the sensitivity analysis for the three different average weights of each container. In practice however, it is rare that containerships with homogenous container loading of 7 tonnes will be considered. Normal homogenous container loads are between 10 tonnes to 13 tonnes. Danish shipowners design their ships with 10 tonnes container load whilst German ship owners tend to use higher average weights of 13 tonnes or even more, Langenberg (174†).

Each of these major items are discussed below not necessarily in order of their merit ranking. The figures in the brackets indicate the percentage changes in the various parameters due to 10% improvement in each of these items.

Steel weight (WS)

It was found that the Required Freight Rate was very sensitive to steel weight. This is because steel weight in containerships is a relatively high fraction of the lightship weight. For the ships considered the steel weight was found to be 72% to 74% of the lightship weight. Also the steel costs are an important part of the ship's First Cost.

One interesting feature of the change in steel weight is its effect on the number of containers able to be carried on deck and the average weight of each container, if the displacement and GM remain constant. In containerships with homogeneous distribution of weight of each container the centroid of the containers is above the centroid of the steel weight. Consequently when steel weight is reduced at constant displacement additional cargo deadweight can be distributed among the containers. However to distribute it at the original centroid of containers would reduce the

+++ Actual service figures may be less.

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<table>
<thead>
<tr>
<th>No.</th>
<th>Item</th>
<th>Units</th>
<th>Initial Values</th>
<th>Final Values</th>
<th>Computer Symbol</th>
<th>RFR £/tonne</th>
<th>% Diff. from basis RFR</th>
<th>Merit Ranking</th>
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<td>%</td>
<td>0.85</td>
<td>0.935</td>
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<td>3.627</td>
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<td>0.88</td>
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<td>4.285</td>
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<td>3045</td>
<td>ENDUR</td>
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<tr>
<td>4</td>
<td>Container handling cost</td>
<td>£/Teu/move</td>
<td>50</td>
<td>45</td>
<td>CHANDLE</td>
<td>39.242</td>
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<td>1.918</td>
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<td>11.89</td>
<td>DIP</td>
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<td>3.308</td>
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<td>7</td>
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<td>years</td>
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<td>LIFES</td>
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<td>4700</td>
<td>WCREW</td>
<td>40.653</td>
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<td>7560</td>
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<td>40.323</td>
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<td></td>
<td></td>
<td></td>
<td>560</td>
<td>504</td>
<td>CLUBCY</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>470</td>
<td>423</td>
<td>CLUBSY</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>gms/bhp-hr</td>
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### Table 14.2 (Contd.)

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<td>14</td>
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<td>years</td>
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<td>12</td>
<td>LIFEC</td>
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Basis ship. Container Capacity 1500 Teu, speed 21 knots, North Atlantic Route, 2 ports of call, average weight of each container = 10.5 tonnes without ballast.

\[
L_B = 216.235, \quad B = 30.190, \quad T = 8.375, \quad D = 20.375, \quad Cb = 0.607
\]

Life of Ship and Life of Container increased by 4 years

Steel weight estimation method 4 option used (Section 6.1)

Dimensions in metres.
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<th>No.</th>
<th>Item</th>
<th>Units</th>
<th>Initial Values</th>
<th>Final Values</th>
<th>Computer Symbol</th>
<th>RFR £/tonne</th>
<th>% Diff. from basis RFR</th>
<th>Merit Ranking</th>
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<td>DIST</td>
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<td>years</td>
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<td>WCREW</td>
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<td>British hp</td>
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<td>17998</td>
<td>SHP</td>
<td>65.737</td>
<td>3.931</td>
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<td>72</td>
<td>COFUEL</td>
<td>67.513</td>
<td>1.336</td>
<td>12</td>
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(Contd.)
Table 14.3 (Contd.)

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<th>Computer Symbol</th>
<th>RFR £/tonne</th>
<th>% Diff. from basis RFR</th>
<th>Merit Ranking</th>
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</thead>
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<td>14</td>
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<td>£/hr</td>
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<td>3.487</td>
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Basis ship. Container Capacity 1500 Teu, speed 21 knots, North Atlantic Route, 2 ports of call, average weight of each container = 7 tonnes.

\[
\begin{align*}
L_{BP} & = 233.611, \quad B = 28.668, \quad T = 7.186, \quad D = 19.523, \quad Cb = 0.607 \\
\text{Life of ship and Life of container increased by 4 years.}
\end{align*}
\]

Steel weight estimation method 4 option used (Section 6.1)

Dimensions in metres.
Table 14.4. Summary of Sensitivity Analysis for different average weight of each container.

<table>
<thead>
<tr>
<th>Item</th>
<th>% Diff. from basis RFR</th>
<th>% Diff. from basis RFR</th>
<th>% Diff. from basis RFR</th>
<th>% Diff. from basis RFR</th>
<th>Merit Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Weight of Container</td>
<td>14</td>
<td>10.5</td>
<td>7</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Basis RFR £/tonne</td>
<td>28.867</td>
<td>40.447</td>
<td>68.427</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load Factor</td>
<td>3.772</td>
<td>3.627</td>
<td>3.452</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Round Voyage distance</td>
<td>4.223</td>
<td>4.285</td>
<td>4.577</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Container handling cost</td>
<td>2.938</td>
<td>2.979</td>
<td>3.038</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Ship's First Cost</td>
<td>1.939</td>
<td>1.918</td>
<td>1.939</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Port-time per round voyage</td>
<td>3.267</td>
<td>3.308</td>
<td>3.512</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Ship's life</td>
<td>1.330</td>
<td>1.315</td>
<td>1.328</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Average crew wages</td>
<td>0.471</td>
<td>0.479</td>
<td>0.482</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Installed power</td>
<td>2.865</td>
<td>3.219</td>
<td>3.931</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Total port costs</td>
<td>0.374</td>
<td>0.383</td>
<td>0.386</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Gross Register tonnage</td>
<td>0.297</td>
<td>0.306</td>
<td>0.305</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Fuel oil costs</td>
<td>1.548</td>
<td>1.476</td>
<td>1.336</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Specific fuel consumption</td>
<td>2.123</td>
<td>2.185</td>
<td>2.489</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Labour wage rate</td>
<td>0.921</td>
<td>0.929</td>
<td>0.963</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Operating costs</td>
<td>5.785</td>
<td>5.771</td>
<td>5.685</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Steel wt.</td>
<td>7.874</td>
<td>10.493</td>
<td>18.437</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Steel cost</td>
<td>0.277</td>
<td>0.274</td>
<td>0.297</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Cost of Container</td>
<td>2.362</td>
<td>2.396</td>
<td>2.464</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>No. of sets of containers</td>
<td>2.362</td>
<td>2.396</td>
<td>2.464</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Life of container</td>
<td>3.346</td>
<td>3.389</td>
<td>3.487</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>
GM. Consequently if displacement is maintained the number of containers above the deck must be reduced to reduce their centroid although the average weight of each container will increase.

This characteristic is not present in most ships where the centroid of the cargo is generally below that of the steel weight and a reduction in steel weight will generally increase both deadweight and stability.

Containerships are stability limited ships and attain their deadweight requirements at drafts less than that allowable by the geometric free board. Therefore the ratio of cargo deadweight to steelweight will be a smaller fraction compared to a deadweight limited ship. Consequently, a 10% change in steelweight will have a larger impact on the change in cargo deadweight in containerships compared to deadweight limited ships. This is illustrated in Table 14.4 which shows that for ships designed for average weights of container of 14.0, 10.5 and 7.0 tonnes the change in RFR for 10% reduction in steel weight progressively increases as the average container weight reduces. Selective stowage of containers can result in improving stability and the subject is considered in Section 13.2. The program is not able to consider selective stowage without further development.

In the program a reduction of 10% in steelweight causes the number of containers on the deck to reduce by 2, 3 and 21 for ships of weight of each container 14, 10.5 and 7.0 tonnes respectively because of stability considerations. The additional deadweight allows the weight of each container to rise to 14.92, 11.41 and 8.07 tonnes respectively. The cargo carried per annum therefore rises by 7.8%, 11% and 21% respectively. The reduction in steel weight also reduces the first cost of the ship by 3%. Therefore the value of RFR reduces.

The sensitivity of RFR with reduction in steelweight also shows that better estimating equations than those used in this thesis need to be developed. The steelweight estimation method developed by Chapman in 1969 results in
higher steel weight than is the case for recently built containerships. Moreover a German shipbuilder, Blohm and Voss when approached for guidance on weight and centre of gravity of containerships confirmed that weight discrepancies ranging around 10% were found on containerships which were built to the same main dimensions and same specification at different shipyards. It was also found by the shipyard that weight and centre of gravity cannot be put into simple formulae because these depend very much on individual hull structure and shipyard practice. Although some guidance was obtained from the shipyard in the form of graphs, it was difficult to translate them to a form suitable for computer programs.

Watson & Gilfillan's method of steelweight estimation depends very much on the choice of value of K (see Section 6.1 method 8).

To apply this method the value of K has to be derived from a basis ship of dimensions closer to the ship whose steelweight has to be estimated. For a study such as this where a very wide range of ship size and speed were studied, it was not possible to rationalise the value of K with the limited data that was available.

Reduction in steel weight can be achieved by considering either the single skin structure or the trunk type structure as proposed by Langenberg (36). The weight of hull structure in single skin construction can be expected to be about 6 per cent lower and in trunk type about 4 percent lower than the conventional double skin structure (36). A more careful approach to design e.g. 'Design for production' might save steel weight and a two or three percent reduction in lightship displacement could be achieved, especially if more higher tensile steel is adopted (202).

Operating Costs (TRCOS)

The operating cost includes the daily running costs, voyage costs and container handling costs but excludes the cost associated with operating the required sets of containers.
The influence on RFR due to reduction in operating cost is quite significant.

A 10% improvement in operating costs is more readily attainable since a shipowner has more direct control over the operating costs. A 10% improvement might be achieved either by reducing the fuel bill by selection of a main engine of lower specific fuel consumption or by reduced manning with engine room automation.

Round voyage distance (DIST, ENDUR)

The round trip distance (DIST) was 6770 n. miles and endurance (ENDUR) was assumed to be half this distance. A decrease in Round voyage distance reduces the time spent at sea by 1.3 days. Fuel costs are reduced by 2% but there is an increase in port costs and container handling costs (5%) which increases the total operating costs by (2.5%). Cargo carried per annum also increases by about 6% due to the increase in the number of round trips per annum. It is less easy to propose a reduction in this parameter. It is a mixture of distance travelled and time taken. Some improvement may be possible by close attention to weather routing. Great circle sailing is shown to be necessary unless weather influences are much against it.

The importance of this feature indicates that a reduction of ports of call may be an advantage but that advantage could be suboptimum when considered as a part of the wider transport system. It also encourages serving a country by one port to reduce coasting time.

Load factor (ALFO, ALFI)

Increasing the load factor by 10% increases the port time (9%) and decreases the number of round trips/annum (4%). Increase in port time increases the port costs (1.6%) and the reduction in the number of round trips/annum reduces the fuel costs (2%). The increase in load factor increases the
container handling costs (5.3%). The overall operating cost however increases by merely 2.5%. Increasing the load factor also increases the amount of cargo carried per annum (5.2%) which more than offsets the detrimental effect of increased port time on RFR. In real life an improvement of 10% on load factor is rarely achievable. This is either due to the uneven flow of cargo in outbound and inbound legs of the round voyage whereby increasing cargo on one leg of the journey will have less impact on the overall load factor or due to overtonnage on certain routes. A realistic assumption of load factor would be 68% under open competition but by better balancing of demand and supply under co-ordinated competition a load factor of 85% might be achievable (130).

Another possibility is to make additional calls at one or more ports to get more cargo but with the attendant increase in the distance steamed. A trade-off between the extra revenue gained and the extra costs incurred may show this to be an economic choice.

Life of container (LIFEC)

A container life of 8 years was thought to be a reasonable assumption when the first purpose built containerships came into service. Presently it is thought to have a life of 12 to 15 years. There is no clear indication as yet on what the life of a container should be (see Section 11.5). This is mainly due to the fact that it is nearly 12 years (1968-1980) since the first generation of purpose built containerships came into operation which is less than the expected life. Moreover shipowners usually undertake major refurbishing so as to extend the life of the containers. Since in the model a new set of containers is added every 8 years, a large amount of negative cash flow occurs earlier than it would if the container life was extended to 12 years. This indicates that the present policy of shipowners to refurbish steel containers every 5 years (Section 11.3) is based on sound economic judgement.
Port time (DIP)

The proportion of port time to sea time of container ships is governed by the round voyage distance, the number of ports of call and the number of containers loaded and unloaded. The North Atlantic Route is a short route and it is assumed that the containership loads and unloads all of its containers at each end of the sea leg. This means that the ship considered spends roughly equal time at sea and in port.

Reduction in port time like the round trip distance increases the number of round trips per annum (5%). This in turn increases the fuel costs (3%), container handling costs (5%) and port entry and exit costs (5%). Port daily costs are reduced (5%) because of shorter port time and the overall port costs are reduced by 2%. The operating costs increase by 3% but the increased number of round trips/annum increases the amount of cargo carried per annum (5%) which more than offsets the increased cost of operation.

The importance of port time on longer routes will be less pronounced since the proportion of port time to sea time will be appreciably lower for this type of ship.

Container handling cost (CHANDL)

Container handling cost forms nearly 50% of the total operating cost. A 10% improvement in container handling costs reduces the operating costs by 5%.

Container handling costs are more or less uniform worldwide. Thus a change of container route will not bring about significant change in container handling costs. A 20' container costs as much to handle as a 40' container and there are hardly any rebates, except in a few ports (see Section 10.9), for empty containers. Therefore reduction in handling costs cannot be achieved either by a cargo mix of 20' and 40' container or by a reduction of the load factor.
However more sophisticated routing control of containers themselves may minimise the carriage of empties. Ports with flexibility of labour are to be preferred.

Installed power (SHP)

A 10% reduction in installed power reduces the machinery weight (7.8%) and the weight of fuel (8.5%). In a similar manner to reduction of steel weight the number of containers from the deck are reduced by 3, 5 and 8 for containership designed with average weight of each container 14, 10.5 and 7 t. The average weight of each container is able to rise by 0.8 t, 1 t and 1.4 t respectively. There is reduction in material cost (3.5%), cost of labour (1.5%) and cost of ship by (2.5%).

Operating costs reduced by 2% due to reduction in the fuel oil costs (7.5%), machinery maintenance costs (10%) and insurance cost of (2.5%). Cargo deadweight carried per annum increases by 1% to 2%.

Improvements in the installed power are steady but unlikely to achieve a break-through unless methods to reduce frictional resistance substantially, reach fruition. Practical trade off studies between the costs of frequent dry dockings or underwater hull polishing afloat and propeller polishing may indicate the advantage of these measures in reducing the installed power. However reserve power is always required from time to time to maintain schedules and it may be necessary to look carefully at diesel engine design to extend overload running. Standard definition of continuous service power would also be an advantage.

Cost of Container (COSCNT), Number of Sets of Containers (SETCNT)

The cost of containers and the number of sets of containers will have a lesser impact on RFR than extending the life of the containers. A reduction of 10% in the cost of containers is less probable since the cost of containers world wide are more or less uniform at £ 2500 per container.
(1980 cost level). However a larger variation is found in the number of sets of containers required (see Fig. 11.1). With the number of round trips per annum of 13, the number of container sets can vary from 1.8 sets per ship to 3.5 sets per ship depending on the frequency of service and the box turnaround time. Therefore reductions in the required number of sets of containers per ship is more probable.

Specific fuel consumption

A reduction in specific fuel consumption reduces the weight of fuel (10%) and the cost of fuel (10%). Similar to reduction in steelweight and installed power, the reduction in weight of fuel results in loss of 3 containers from the deck with negligible effect on the cargo deadweight.

Its effect on operating costs has ensured that steam machinery with its inherently higher fuel consumption is not being fitted in new vessels and is being replaced by diesel engines in existing ones. The benefit of relatively cheaper fuel in steam engines is quite outweighed by relatively higher fuel consumption when compared with diesel machinery.

Great effort is being made among diesel engine manufacturers to reduce fuel consumption and the present trend is towards uniflow scavenged long bore engines with very low RPM. The benefits in propeller efficiency from low RPM remain an important aspect of fuel economy.

Ship's First Cost (CAPCOS)

Container ships usually have very high values of First Cost because they are relatively sophisticated vessels. In unusual economic circumstances the purchase price may be below the cost but such circumstances either correct themselves by bankruptcy or become a permanent subsidy and thus essentially a lower first cost. Practical reduction in First Cost must include very careful scrutiny of specifications to ensure that unnecessary items are omitted, value is obtained
for necessary items and any breakthroughs in new materials or cost of items are exploited. The other main source of reduction is that of exploiting to the full competitive pressures and state intervention. Also a reduction in First Cost reduces risk as it limits the amount of immediate investment.

Fuel Oil Costs (COFUEL, CDESL, CLUBSY, CLUBSY)

Fuel oil cost is about 27% of total operating cost and a 10% reduction in fuel cost will reduce operating cost by 2.5%.

Between 1973 and 1980 the price of fuel oil has increased by a factor of 7.7 and diesel oil by a factor of 8.5. Substantial fuel price increase usually results in lower economic speed as previously considered. The longer voyage times that result from lower speed increase crew costs and capital costs on a tonne mile basis. Since fuel prices are very liable to increase it would be important for the design to be as insensitive as possible to these increases which might otherwise demand premature slow steaming, a competitive disadvantage.

Life of Ship (LIFES)

An extension to the life of the ship has little effect on a comparison that uses present worth as does RFR, for with the high interest rates now common a future beyond twenty years has little influence. Perhaps this is more a weakness in the measure of merit than an accurate observation, for vessels aged twenty today are kept in service as long as they are profitable. Much must depend on technological change. If hull sizes and shapes are not profoundly influenced by change, re-engining and re-equipping may become commonplace, as a means of securing an effectively new ship at low cost. Certainly much change in the area of machinery and equipment is to be expected but technological obsolescence may very well
overwhelm the whole vessel. If the life of the ship is to be preserved beyond twenty years more allowance for old age may need to be made in the new vessel with consequent increase in Capital Cost.

Shipbuilding Labour Wage Rates (WR)

A 10% improvement in labour wage rates decreases the labour costs by 10% and the capital cost by 5.0%. A shipowner has a choice here for improvement by placing his order in a country with lower wage rates and for a shipbuilder it shows that a decrease in labour costs can have significant effects on the overall economics of the ship. Improvements in labour productivity will have the effect of reducing the wage rate but with so many labour overhead costs dictated by government labour legislation, wage rates are liable to increase.

Wages of Crew, Petty Officers and Officers (WCREW, WPO, WOFF)

Crew costs which is normally 57% of the daily running costs, can vary by a factor of 8 for ships under different flags. Therefore a shipowner has more scope to achieve a 10% reduction if the political climate allows him, or the legal or national boundaries no longer constrain him, from selecting crew from the developing world with attendant lower costs. However a 10% improvement in crew costs brings about only 1% reduction in the operating costs.

The daily operating costs are crew costs, maintenance and repairs, hull and machinery, insurance and stores and provisions. Excluding crew costs the magnitude of other costs will vary little between similar ships of any flag engaged in a similar trade assuming a standard level of operating efficiency. Therefore a shipowner usually seeks a reduction in crew costs by either employing crew with lower wage demands or by reducing the number of crew where this is not possible and promoting interchangeability of crew within each ship.
Port Costs (CPORT)

Port costs form nearly 6.5% of the operating costs for the basis ship. Therefore a 10% improvement in port costs reduces the operating costs by 0.65%. Port costs will vary from port to port and will also depend upon the number of ports of call. Large variations in port costs are possible, even a factor of 10 (see Section 10.7). Although a shipowner will have little choice in influencing directly the port costs except perhaps by rebates given by certain port authorities which are negotiable. A considerable saving may be achieved by omitting certain ports of call with attendant benefit of lower steaming distance. But this must be traded off against any loss of earnings. The significance on the RFR is low, showing that simpler equations than those developed in this thesis may be incorporated in the program e.g. port costs expressed as a function of net registered tonnage.

Gross Registered Tonnage (GRT)

The total port costs were made a function of GRT, therefore a 10% reduction in GRT will decrease the port costs by (6.5%) and the operating costs (0.5%). There is little to be gained in reducing the GRT since port costs have little significance on the RFR. No great change is expected with the 1969 tonnage regulations.

Steel Costs (STLCOS)

A 10% reduction in the cost of a tonne of steel reduces the total material cost (3%) and the total cost of the ship (1.5%). The hull insurance and the war risk insurance reduces by the same amount but has negligible effect on the operating costs.

Containerships require some high tensile steel and some areas need attention to the notch toughness of the steel, consequently such vessels cannot take great advantage of a market surplus of mild steel. Ultimately greater efficiency within the steel industry may particularly benefit container-
ships. Steel pricing is a complicated function of amount, sizes and quantity. The builder by care in construction methods and by minimising scrap may be able to secure reduction in steel costs.

14.3.2. Variation in number of ports, ship size and speed.

(Case 1)

Ships of container capacity 1000 Teu, 1500 Teu and 2000 Teu were selected to study the effect of increasing the number of Ports on Required Freight Rate. The speed of the ships were varied from 15 knots to 27 knots with a step size of 3 knots. Fig. 14.18 shows the effect of increasing the number of ports of call on the Required Freight Rate with changing ship size and speed. Fig. 14.19 shows the effect of increasing the ship's speed on the Required Freight Rate with changing ship size and the number of ports of call. Fig. 14.20 shows the effect of increasing the ship's size on the Required Freight Rate with changing speed and number of ports of call.

The rate of change of RFR with increasing number of ports of call is linear. The economy of scale of ship size at all speeds is apparent from the lower slopes of the lines with increasing ship size (Fig. 14.18).

The rate of change of RFR with increasing speed has a less pronounced effect on bigger ships compared to the smaller ships (Fig. 14.19) and at higher speeds of 27 knots for 4 and 8 ports of call (Fig. 14.20) ships above 1850 Teu show a lower Required Freight Rate.

For speeds up to 21 knots the 1500 Teu ship shows a lower Required Freight Rate for 8 ports of call (Fig. 14.19, Fig. 14.20). At higher speeds of 27 knots and increasing number of ports of call the larger ships above 1850 Teu are able to carry more cargo per annum which more than offsets the higher operating and capital costs and therefore show a lower Required Freight Rate.

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Fig. 14.18 Variation in number of ports, ship size and speed.
(Number of ports versus Required Freight Rate)
Fig. 14.19 Variation in number of ports, ship size and speed.

(ship speed versus Required Freight Rate)

1000 Teu

1500 Teu

2000 Teu

Number of ports

12

8

4

2

Required Freight Rate £/tonne

Speed in Knots
Fig. 14.20 Variation in number of ports, ship size and speed. (Ship size versus RPR.)

Required Freight Rate £/tonne

15 Knots
18 Knots
21 Knots
24 Knots
27 Knots

Number of ports

12
8
4
2

Container capacity in Teu

1000 1500 2000

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14.3.3. Variation in delays, ship size and speed (Case 1).

The effect of delays in port on the Required Freight Rate was studied for ships of similar container capacity and speed as given in the previous section. The delay in port, was associated with any type of delay caused over and above the required time in port. Delays of one to five days were introduced.

Figure 14.21 shows the effect of increase in delay on the Required Freight Rate with changing ship size and speed.

Figure 14.22 shows the effect of increasing speed on the Required Freight Rate with changing ship size and delays of 3 and 5 days. It was assumed in Section 14.1 that there was no delay in port over and above the port time required for berthing/unberthing and loading/unloading the ship.

Figure 14.23 shows the effect of increasing the ship size on the Required Freight Rate with changing values of ships speed and delays.

Like previous sections the economy of scale in ship size is shown by the lower slopes of the lines of Required Freight Rate with increase in delay. This rate of increase in the RFR with delay is linear (Fig. 14.21).

Ships of 1500 Teu show a clear advantage over other ship sizes for speeds up to 27 knots for delays of 3 days (Fig. 14.22). For delays of 3 and 5 days at speeds higher than 24 knots, ships above 1900 Teu give a lower Required Freight Rate (Fig. 14.22, Fig. 14.23) than the 1500 Teu ship.

With increase in port time the port costs increase, but time spent in port does not much affect the optimal speed (Fig. 14.22) although it increases the cost per tonne mile and increases in these factors, therefore, tend to accentuate the penalty paid if the ship is operated away from its optimal speed. However a decrease in port time encourages higher speeds due to the higher proportion of sea time where the speed could be used.
Fig. 14.21. Effect of delays on ship size, speed and Required Freight Rate
(Delay versus Required Freight Rate)

1000 Teu

1500 Teu

2000 Teu

Delay in days

Required Freight Rate £/tonne
Fig. I4.22 Variation in ship size, speed and delays. 
(ship speed versus Required Freight Rate)

Required Freight Rate £/tonne

Delay in days

1000 Teu

1500 Teu

2000 Teu

ship speed in Knots
Fig. 14.23 Variation in ship size, speed and delays
(ship size versus Required Freight Rate)

- 15 Knots
- 18 Knots
- 21 Knots
- 24 Knots
- 27 Knots

Required Freight Rate £/tonne

Container capacity in Teu
14.3.4. Variation in Discount Rate, Income Tax and Ship's Life (Case 1).

A ship of container capacity of 1500 Teu and a speed of 21 knots was used to study the effect of variation of Discount Rate and Income Tax on the Required Freight Rate and determine the optimal life of the ship.

Fig. 14.24 shows the effect on the Required Freight Rate with increasing or decreasing ship's life for various values of Income Tax Rate and Discount Rate.

For the basis ship at 15% Discount Rate and 52% Tax, there is little advantage in extending the life of the ship beyond 24 years. Lowering the Discount Rate to 10% extends the life of the ship beyond 29 years but at those levels of profitability (or implied income) the shipowner will not be willing to invest in new building.

Lowering or raising the value of money or Discount Rate has more effect on the Required Freight Rate than the Tax Rate. Large variations in Tax Rate from no tax position to 75% Tax Rate have less pronounced effect on RFR than doubling the Discount Rate from 10% to 20%.

Free depreciation is assumed in the thesis which means a shipowner is allowed to write off his capital allowances against profit as quickly as profits permit. For some part of the ship's life a shipowner does not pay any taxes therefore the influence of Tax Rate on RFR is less pronounced. It may remain an advantage to pay tax if substantial investment grants exist as a part of the tax system.
CHAPTER 15
EVALUATION OF RISK IN MARINE CAPITAL INVESTMENT

15.0 INTRODUCTION

15.1 APPROXIMATE ESTIMATE OF RISK
  15.1.1. SENSITIVITY ANALYSIS IN THE DETERMINISTIC APPROACH
  15.1.2. SENSITIVITY ANALYSIS IN THE PROBABILISTIC APPROACH
  15.1.3. RANKING OF INFLUENCING VARIABLES

15.2. PROBABILISTIC APPROACH TO RISK ANALYSIS
  15.2.1. ANALYTICAL APPROACH
  15.2.2. OTHER METHODS
  15.2.3. MONTE CARLO SIMULATION
  15.2.4. DEFINING DISTRIBUTION OF UNCERTAIN VARIABLES
  15.2.5. DEALING WITH DEPENDENCIES

15.3. APPLICATION OF RISK ANALYSIS TO CAPITAL INVESTMENT
  15.3.1. COMPUTER ALGORITHMS
  15.3.2. PROGRAM STRUCTURE & INPUT/OUTPUT
  15.3.3. REQUIRED FREIGHT RATE ASSUMING NO DEPENDENCIES
  15.3.4. REQUIRED FREIGHT RATE ASSUMING DEPENDENCIES
15.0 INTRODUCTION

In the last chapter sensitivity analysis was used to identify the variables which had most influence on the Required Freight Rate. A sensitivity analysis for a predefined improvement of 10% was used for this purpose. It was pointed out that in real life a 10% improvement of some of the variables may not be possible. The importance of the uncertainty surrounding each of these variables was identified by merit ranking of the variables and it was explained that effort needs to be expended in getting a better estimate of those variables which had significant influence on RFR.

To account for uncertainty surrounding some of these variables and also to assess the influence of each of these variables on RFR, based on possible variation, rather than an arbitrary 10% variation, a new technique is introduced.

This new technique involves carrying out a sensitivity analysis based on three possible estimates. The user needs to supply, besides the best estimate of a variable as in computer Model I and Model II, two other estimates. These are the 'pessimistic' estimate and the 'optimistic' of a variable. These three values of a variable, representing the uncertainty and also their possible variation are used by computer Model III for merit ranking. Computer Model III forms an extension to the Computer Model I. It also shows how the total risk involved in undertaking a capital investment in containerships can be assessed by Computer Model III. Computer Model III also identifies in an approximate way, the contribution of each of the variables to the overall risk.

'Pessimistic' and 'optimistic' estimates provide an indication of the uncertainty surrounding the best estimate made for a particular variable but, for a complete description of the uncertainty, a probability distribution is required. This is derived by Monte Carlo simulation using Computer Model IV. The usefulness of generating a risk profile of the RFR is indicated together with how dependencies between variables can be ascertained.
15.1. APPROXIMATE MEASURE OF RISK

There are various ways to account for Risk in a deterministic approach to evaluate alternative designs. A few of them are mentioned here.

(a) Pay back Period Method
(b) Risk adjusted Discount Rate
(c) Making conservative adjustment to data values
(d) Raising the minimum acceptable rate of Return
(e) Running Multiple cases.

The various disadvantages of these methods are given by Klausner (204). All the methods a), c), d), e) do not account for risk explicitly and thereby obscure the true risk involved in the capital investment. The most common of these methods is the risk adjusted Discount Rate, which accounts for risk explicitly and is discussed briefly below.

Subjectively discounting for risk

In this technique the acceptable rate of return to reflect the degree of uncertainty felt about the investment outcome is incorporated by discounting at this rate of return. The less certain the investment data values or greater the risk involved the higher the minimum acceptable rate of return. As a consequence, the specification of the appropriate interest rate becomes a matter of subjective judgement without clarifying the risk inherent in the nature of the capital investment and herein lies the principal weakness of the technique.

15.1.1. SENSITIVITY ANALYSIS IN THE DETERMINISTIC APPROACH

This is the traditional approach which was applied in the deterministic stage using Computer Model I and Model II. Most of the estimates of the cost items, weight items and other input variables such as load factors and number of sets of containers were best estimates. Some degree of uncertainty was incorporated by carrying out a sensitivity analysis to identify the variables which had the most influence on the RFR. Further effort is then spent in getting better
estimates of only these items. In addition several such sensitivity analyses can be carried out by replacing the best estimates by their pessimistic or optimistic values. The basic idea is simple: if a change in a variable has very little effect on the RFR, then the investment decision is not likely to depend to any great extent on the accuracy of the estimate of that variable. On the other hand, if a change in the estimate produces a large change in the RFR then the uncertainty surrounding the variable may well be a significant consideration when the investment decision is being made. Thus sensitivity analysis can be regarded as a way of quickly identifying those variables which contribute most to the risk of the investment.

The first disadvantage of this model is that it is subject to bias, which occurs if some statistic such as the median or mode is used as the 'best' estimate instead of the expected value (mean) (205).

The model does not formally include uncertainty, and only crude ideas of risk can be obtained. Using pessimistic estimates for all factors, for example, may give an idea of RFR if all goes wrong, but the probability of this occurrence, or the probability of more realistic estimates, is hard to evaluate by sensitivity analysis.

The major disadvantage of sensitivity analysis is that the 10% changes in the most likely estimates may not be directly comparable. For example, a 10% change in operating cost estimate might be quite reasonable, whereas a 10% change in the distance between ports of call may not be achievable. The next section will show how this can be overcome by a new method of sensitivity analysis.

It is also customary to consider only changes in one variable at a time. (The other variables in sensitivity analysis are assumed to be at the 'best' estimates). The effects on the RFR of combinations of changes in different variables is, therefore, largely ignored (4).
A methodological difficulty with sensitivity analysis arises when there is a dependence between two variables, because then it is not strictly correct to consider changes in only one variable at a time (4).

15.1.2. SENSITIVITY ANALYSIS IN THE PROBABILISTIC APPROACH

The ideas presented in this section were developed by Hull '80 (4). Required Freight Rate was the measure of merit selected.

The objective function is then expressed as

\[ RFR = f(X_1, X_2, X_3, \ldots, X_n) \]

which is a non-linear function of independent and dependent variables \( X_1, X_2, X_3, \ldots, X_n \). Some of the variables are uncertain variables. A sensitivity analysis generally calculates for a certain variable \( j \):

\[ \Delta RFR = f(E_1, E_2, \ldots, E_{j-1}, E_j + \Delta E_j, E_{j+1}, \ldots, E_n) - f(E_1, E_2, \ldots, E_n) \]

where \( E_j \) is the most likely estimate of \( X_j \) and \( \Delta E_j \) is a change in the value of \( E_j \). For sensitivity analysis in the deterministic approach the value of \( E_j \) is usually taken as a fixed percentage of the variable such as a 10% improvement. A methodological difficulty with such an approach is that a 10% improvement in distance is not directly comparable to a 10% improvement in say operating costs primarily because a 10% improvement in operating costs is conceivable whereas in distance it is not. In this new approach the user inputs, besides the most likely estimate two other estimates. These are the pessimistic and the optimistic estimates.

Table 15.1. Sensitivity Analysis, Computer Model III.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Most Likely Estimate</th>
<th>Optimistic estimate</th>
<th>Pessimistic estimate</th>
<th>RFR for optimistic estimate</th>
<th>RFR for pessimistic estimate</th>
<th>(RFR - RFR⁺) Range of RFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>
For each of the variables Table 15.1 shows,
(a) The values of RFR when the variable is equal to its optimistic estimate, all other variables being equal to their most likely values (col. 5).
(b) The values of RFR when the variable is equal to its pessimistic estimate, all other variables being equal to their most likely values (col. 6).
(c) Range of RFR, difference of values of RFR in col. 5 and col. 6.

The final column in this table provides a set of numbers which are directly comparable.

The definition of the terms 'optimistic estimate' and 'pessimistic estimate' deserve some consideration. It is not necessary for the optimistic estimate to be the 'best conceivable' value for the variable and for the pessimistic estimate to be the 'worst conceivable' value. It is however necessary to be consistent in the use of the terms. In this thesis it is assumed that $U_j$ is equal to the higher of the optimistic and pessimistic estimates, and $L_j$ is equal to the lower of the two. The optimistic estimate for a variable is not always higher than its pessimistic estimate for example variables such as costs the reverse is true.

The difference between $U_j$ and $L_j$ is referred to as the range of variable $j$ and $S_j$ is the sensitivity coefficient. Where $S_j$ ($j = 1, n$) can be defined as

$$S_j = f(E_1, E_2, \ldots, E_{j-1}, U_j, E_{j+1}, \ldots, E_n) - f(E_1, E_2, E_{j-1}, L_j, E_{j+1}, \ldots, E_n)$$

and can be used to provide an indication of the relative importance of different variables.

A simple linear Model

If the RFR is considered to be a linear Model, then it can be expressed as

$$RFR = f(X_1, X_2, \ldots, X_n) = \sum_{j=1}^{n} a_j X_j$$

Eq. 15.4
where $a_j$'s are constant and $x_j$'s are independent. This model is appropriate in relatively simple situations, for example where each of the $X_j$ represents an inflow or outflow of cash. However, it is worth examining the model in detail because it suggests results which might be approximately true in a wide range of situations.

It is easy to see that the model implies

$$S_j = a_j(U_j - L_j) \quad \text{Eq. 15.5}$$

Further

$$\mu_{RFR} = \sum_{j=1}^{n} a_j u_j \quad \text{Eq. 15.6}$$

and

$$\sigma_{RFR}^2 = \sum_{j=1}^{n} a_j^2 \sigma_j^2 \quad \text{Eq. 15.7}$$

where $\mu_{RFR}$ and $\sigma_{RFR}$ are the mean and standard deviation of $RFR$ and $\mu_j$ and $\sigma_j$ are the mean and standard deviation of $X_j$. Defining

$$K_j = \frac{\sigma_j}{U_j - L_j}$$

for all $j$ it follows from eq. 15.5 and eq. 15.7 that

$$\sigma_{RFR}^2 = \sum_{j=1}^{n} K_j^2 S_j^2 \quad \text{Eq. 15.8}$$

This is an interesting result as it shows that an estimate of $\sigma_{RFR}^2$ can be obtained from the sensitivity coefficients and estimates of $K_j$'s. If it is assumed that $K_j$ is approximately constant for all $j$, that is, standard deviation of a variable is approximately proportional to its range, then Eqn. 15.8 implies that it is the square of the sensitivity coefficient of variable $j$ which in effect determines the contribution of the variable $j$ to $\sigma_{RFR}^2$. Therefore it implies that if one variable has half the sensitivity coefficient of another variable then its contribution to $\sigma_{RFR}^2$ will be
one-quarter as much and that less sensitive variables contribute very little to the overall uncertainty.

Hull (4) 1980 who developed this technique applied the above linear model to four well documented case studies. All the case studies involved cash flow models which were non-linear. One of these models was highly non-linear. The objective function RFR given by Eq. 15.1 is also non-linear; not a simple non-linear problem, but one which cannot even be approximated by a series of linear segments. 'Highly non-linear' would be an appropriate term to use (206).

Approximate value of standard deviation of the Required Freight Rate

The first key result produced for the linear model was

\[ \sigma_{RFR} = \sqrt{\sum_{j=1}^{n} K_j^2 S_j^2} \]  

Eq. 15.9

Application of this relationship to the non-linear models by Hull (4) showed that if variables are independent, Eq. 15.9 gives an approximate measure of the standard deviation of the measure of merit.

Therefore to estimate \( \sigma_{RFR} \) it is necessary to provide

(a) the estimates \( U_j \), \( L_j \) and \( E_j \) for each variable and

(b) estimate \( K_j = \frac{\sigma_j}{U_j - L_j} \) for each variable \( j \).

Estimating \( K_j \) is not straightforward. Assuming that \( L_j \) corresponds to 0.05 fractile and \( U_j \) corresponds to 0.95 fractile a reasonable value of \( K_j \) is 0.30 for a normal distribution (4).

Therefore the total risk involved in a capital investment in ships as defined by \( \sigma_{RFR} \) can be evaluated by using this form of sensitivity analysis.

Approximate value of the mean of the Required Freight Rate

The usual approach, as applied in the deterministic stage of the design, to obtain the best estimate of RFR is to combine together best estimates of the individual variables, that is

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where $E_1, E_2, \ldots, E_n$ are the best estimates of the variables. However Hull (4) has shown that this can lead to serious errors particularly when some distributions are skewed. This is because the best estimate of a variable corresponds to its mode and not to its mean. Also the best estimate of a function is not always the function of the best estimates of the variables (207). Therefore,

$$\mu_{\text{RFR}} = f(E_1, E_2, \ldots, E_n)$$  \hspace{1cm} \text{Eq. 15.10}

should be preferred to Eq. 15.10 for calculating the best estimate of Required Freight Rate.

The mean of the individual variables is then derived from the following formula often used in PERT applications

$$\mu_j = 1/6(L_j + 4E_j + U_j)$$  \hspace{1cm} \text{Eq. 15.12}

This approach is adopted for calculating the expected mean value of RFR.

**Computer Model**

FORTRAN computer codes for carrying out the above sensitivity analysis were developed by Hull (4) 1980. These were modified to suit the requirements of the preliminary ship design problem. The overall program structure is shown in Fig. 15.1. Two subroutines were written for this analysis. These are the subroutine subprograms FUNCTN and CONSTR as developed in computer Model II in the deterministic phase. The subroutine subprogram SENPAR, SENVIT and SORT were modified and adopted from Hull (4) 1980. The main program of computer Model I, was modified to read three values of the input variables. The functions of the various subprograms are discussed below.

a) **Main program.** This program is the same as in computer Model I and Model II, except that three estimates of each variable are input for which the sensitivity analysis is to be carried out. A sample input data list is shown in Fig. 15.2.
Fig. 15.1. Program structure probabilistic phase, to carry out sensitivity analysis, measure of risk and ranking of variables in order of importance.

(Computer Model III)

- Read in ship characteristics + other data input values of three estimates for primary variables (6293)

- Subroutine SENVIT (4336)
  - SUBROUTINE SENPAR (476)
  - SUBROUTINE FUNCTN (3298)
  - SUBROUTINE CONSTR (3222)
  - SUBROUTINE SORT (234)

(Figures within brackets indicate the program size excluding common statements, Total = 132 K)
### Fig. 15.2. Input data, sensitivity analysis, container capacity

2250 Teu and speed of 18 Knots

#### SENSITIVITY ANALYSIS

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
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<td>8.00</td>
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<td>2.00</td>
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</table>

INPUT VALUES AS READ IN THE DATA FILE

2250.00 CNT 18.00 V 3383.00 DUR 6766.00 DIST 1.00 PORTF 1.00 PORTD
4NCPLH 0.00 ABAALST 0.03 RGMRB
9.0 SROWS 10.0 FROWS 11.0 STIER 13.0 TIER 0.550SCE 0.700FCB 10.0 SROWS 13.0 TIER
10.00 DMIN14.500 DMAX 0.400V/L 1.500V/L 6.00C/L/B 9.00L/B 2.25B/T 3.75E/T
120.00 REVINS21REVLD21BALAS 11PMC 21STEEL
0.00 ACNT 0.00 ARMANT 0.00 ACINS
0.00 AWARES 0.00 ACRE 0.00 APPOV 0.00 ASTORE
0.00 APIINS 0.00 AHINS 0.00 AADMIN 0.00 ARMANT
0.00 APORT 0.00 AFUEL 0.00 AHANDL

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b) Subroutine FUNCTN. This subprogram calculates the objective function, Required Freight Rate after tax and is the same as used in Computer Model II.

c) Subroutine CONSTR. This subprogram checks if any constraints such as minimum dimensions for a given configuration of midship hold tiers and rows, stability, freeboard, seakeeping and others are violated.

d) Subroutine SENVIT. This carries out the sensitivity analysis by the above technique and also calculates the standard deviation and the mean value of RFR. This subroutine is used to output the results as shown in Fig. 15.3.

e) Subroutine SENPAR. This subroutine is used to store the input variables on which the sensitivity analysis is to be carried out in an array W(I).

f) Subroutine SORT. This subroutine uses a straightforward iterative procedure for arranging in order of influence on RFR, the various variables.

Subroutines, such as those to calculate, the weights, costs and other design parameters are as developed for Computer Model I and Model II in the deterministic phase and shown in Fig. 13.10.

15.1.3. RANKING OF INFLUENCING VARIABLES

A computer program was written for the purpose of carrying out this type of sensitivity analysis. The structure of the main program of computer Model I in the deterministic phase was changed. Thirty six input items were chosen to carry out the sensitivity analysis by computer model III. These items were chosen because of their inherent variability. Items such as distance, specific fuel consumption, and installed power were excluded from this list since these will be known at the initial design stage and by their very nature are not subject to much variation. The influence of major items such as ships First Cost or the operating costs on RFR were left to be determined from sensitivity analysis of the more basic variables of labour wage rates, cost of steel, crew wage rates, and cost of fuel. It was felt that
### Fig.15.3. Output, Sensitivity Analysis, container capacity 2250 Teu and speed of 18 knots

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>BEST ESTIMATE</th>
<th>OPT. ESTIMATE</th>
<th>PESS. ESTIMATE</th>
<th>PERF. MEAS. AT OPT. EST.</th>
<th>PERF. MEAS. AT PESS. EST.</th>
<th>RANGE OF PERF. MEAS.</th>
<th>RANGE COEFF</th>
<th>PERCENT OF WARR</th>
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<td>47.074</td>
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**VALUE OF RFR WHEN ALL VARIABLES EQUAL THEIR BEST ESTIMATES = 38.31**

**VALUE OF RFR WHEN ALL VARIABLES EQUAL THEIR OPTIMISTIC ESTIMATES = 24.34**

**VALUE OF RFR WHEN ALL VARIABLES EQUAL THEIR PESSIMISTIC ESTIMATE = 67.89**

**ESTIMATE OF MEAN OF RFR BASED ON PESS ESTIMATES OF THE MEANS OF VARIABLES = 38.88**

**ESTIMATE OF S.D. OF RFR BASED ON AN S.D TO RANGE RATIO OF 0.5 FOR THE VARIABLES = 3.73**
it is easier to estimate subjectively or objectively the 'pessimistic' the 'most-likely' and the 'optimistic' values of crew wages or labour wage rates than the operating costs and the ship's First Cost.

To assess the variability of say, operating costs, would require the expertise and judgement of an expert. In real life working within the environment of a shipyard design office or with a shipowner's design team this type of co-operation between different departments would be possible. Therefore in real life this technique would incorporate major items like operating costs where the variability could be provided by an expert.

The thirty-six items which were included in the list to carry out sensitivity analysis using Computer Model III are listed below in the sequence shown in Fig. 15.2.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>1</td>
<td>Shipyard's overhead (OVHEAD) as a percentage</td>
</tr>
<tr>
<td>2</td>
<td>Shipyard labour wage rate (WR) in £/hr</td>
</tr>
<tr>
<td>3</td>
<td>Cost of steel (STLCOS) in £/tonne</td>
</tr>
<tr>
<td>4</td>
<td>Material price index (SINDEX)</td>
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<tr>
<td>5</td>
<td>Shipyard's profit (PROFIT) as a percentage</td>
</tr>
<tr>
<td>6</td>
<td>Container handling cost (CHANDL) per Teu per lift</td>
</tr>
<tr>
<td>7</td>
<td>Cost of luboil for cylinder (CLUBCY) £/tonne</td>
</tr>
<tr>
<td>8</td>
<td>Cost of luboil for system (CLUBSY) £/tonne</td>
</tr>
<tr>
<td>9</td>
<td>Cost of diesel oil (CDESL) £/tonne</td>
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<tr>
<td>10</td>
<td>Cost of main engine fuel oil (COFUEL) £/tonne</td>
</tr>
<tr>
<td>11</td>
<td>Average wage of officers (WOFF) £/annum assuming 12 officers</td>
</tr>
<tr>
<td>12</td>
<td>Average wage of Petty officers (WPO) £/annum assuming 6 PO's</td>
</tr>
<tr>
<td>13</td>
<td>Average wage of ratings (WCREW) £/annum assuming 20 ratings</td>
</tr>
<tr>
<td>14</td>
<td>Percentage interest on shipbuilding loan (PCINT) in percentage/annum</td>
</tr>
<tr>
<td>15</td>
<td>Number of years of repayment of loan (YRLOAN)</td>
</tr>
<tr>
<td>16</td>
<td>Steel factor (STEELF), if steel weight estimation method 8 (Section 6.1) was used as the option</td>
</tr>
<tr>
<td>17</td>
<td>Outfit factor (OUFITF), used as an input data for calculating the outfit weight (see Section 6.2)</td>
</tr>
<tr>
<td>18</td>
<td>Ship's life (LIFES) in years</td>
</tr>
</tbody>
</table>
19) Discount Rate (DISCNT) in percent/annum
20) Outbound load factor (ALFO) in percent
21) Inbound load factor (ALFI) in percent
22) Life of container (CLIFE) in years
23) Number of sets of containers (SETCNT)
24) Interest on container financing (CPINT) in percent/annum
25) Cost of a container (COSCNT) in £/Teu
26) Port daily cost factor (PCFD) home ports (Section 10.7)
27) Port daily cost factor (PCFF) foreign ports (Section 10.7)
28) Port entry and exit cost factor (PECFD) home ports (Section 10.7)
29) Port entry and exit cost factor (PECFF) foreign ports (Section 10.7)
30) Labour ratio (RLABF) foreign ports (Section 10.7)
31) Labour ratio (RLABD) domestic ports (Section 10.7)
32) Number of officers (OFF)
33) Number of Petty officers (PO)
34) Number of ratings (CREW)
35) Tax Rate (TAXPCT) in percent
36) Delay in ports (DELAY) in days.

The above is not an exhaustive list, the user can easily add more variables to this input list. Besides these input values which require three estimates as shown in Fig. 15.2, the user must supply the main dimensions of the ship to be studied. Fig. 15.2 is for a ship of container capacity 2250 Teu and a speed of 18 knots. Other input values are the same as in Computer Model I or Computer Model II.

The three estimates required to carry out the sensitivity analysis using computer Model III are the best estimate as in computer Models I and II and the pessimistic and the optimistic estimates of these items.

The computer Model III then calculates the Required Freight Rate for a particular item with the value of the optimistic
estimate of the item while all other items are kept at their best estimates. This procedure is repeated for all the other items in column 1 (Fig. 15.3). A similar procedure is followed and the Required Freight Rate with the pessimistic estimate of the items is calculated as shown in Fig. 15.3, column 6. The range of RFR as defined before is the difference between the RFR calculated with the pessimistic estimate and the RFR calculated with the optimistic estimate. The optimistic estimate for a variable is not always higher than its pessimistic estimate, for variables such as costs the reverse is true. Instead of putting the optimistic estimate of an item in column 3 (Fig. 15.2) and the pessimistic estimate of an item in column 4 (Fig. 15.2) the user can do the reverse. The computer Model III sorts out for each variable which of the final two estimates is the pessimistic estimate and which is the optimistic estimate depending on the value of the RFR and lists them in col. 3 and col. 4 (Fig. 15.3) as output.

The range of the RFR col. 7 Fig. 15.3 is termed the sensitivity coefficient as explained earlier. It is the range of values of RFR which can be produced by varying the value of the items between its optimistic and pessimistic estimate. The range coefficient col. 8 Fig. 15.3 is the sensitivity coefficient col. 7 of the item under consideration divided by the sensitivity coefficient of the most sensitive item, in this case SETCNT. The final col. 9 of Fig. 15.3 shows an estimate of the percentage of the variance of the RFR which is accounted for by the different variables. This is produced on the assumption of linearity as described earlier.

The value of the RFR when all the variables are put equal to their best estimates, is the same as that produced either by computer Model I or Model II, and is shown in Fig. 15.3. Similarly the next two lines of Fig. 15.3 is the value of RFR when all the variables are put equal to their optimistic estimates and pessimistic estimates.
respectively. These two values of RFR are extreme values of RFR and are highly unlikely. The mean value of the Required Freight Rate is shown together with the standard deviation under Fig. 15.3. The derivation of this mean value of the Required Freight was described earlier. The standard deviation is based on the assumption

\[
\text{Standard deviation of the variable} = \frac{\text{Difference between optimistic and pessimistic estimates}}{0.3}
\]

and also described in Section 15.1.2. The figure 0.3 in the above equation can be changed by the user.

The mean estimate of RFR of 38.88 £/tonne based on the PERT type estimate is greater than the value of 38.31 £/tonne calculated by computer Model II. This Required Freight Rate takes account of the variability of each of the 36 variables and reflects the expected Required Freight Rate rather than the best estimate of RFR. This will be the Required Freight Rate that can be expected to be achieved under conditions of uncertainty. The contribution of the variability of the RFR by each of the variables are shown in col. 9.

The ranking of the variables given in Fig. 15.3 is based on the sensitivity coefficient and therefore reduces the variation of each variable to a common denominator. The ranking also takes into account the achievable variation rather than an arbitrary 10% variation as in Chapter 14. It also shows that 62% of the variation of RFR can be accounted for by the first five items on the list; SETCNT, DISCNT, WR, COSCNT, OVHEAD and 98% of the variation of the RFR by the first fifteen items on the list. This gives the user a measure of assessing the importance of elements in the list in relation to the RFR. It shows that most of the effort should be expended in improving say the first five items and what will be left uncertain is the remaining 38% variability of RFR. Assessing the Risk involves the knowledge of the standard deviation of the RFR.

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The standard deviation of the RFR was calculated using the Monte Carlo Technique in computer Model IV, to check the value of standard deviation of 3.73 calculated by computer Model III. Computer Model IV gives a value of $\sigma = 3.317$ (Fig. 15.12) which is very close to the value of $\sigma = 3.73$ calculated by computer Model III. Therefore computer Model III may be used also to assess the total risk inherent in the project.

This type of analysis was also carried out for a containership of capacity 1500 Teu and speed 18 knots. The two methods of steel weight estimation of the program were used in this study. There was uncertainty surrounding the value of the steel factor ($\text{STEELF}$) in the steel weight estimation method by Watson and Gilfillan (35). Fig. 15.4 shows the merit ranking of the variables using Chapman's method (46) for steel weight estimation. The steel factor ($\text{STEELF}$) is shown to be last in the list because it is used as an input data only for steel weight estimation by Watson and Gilfillan's method. Fig. 15.5 shows the merit ranking of the variables using Watson and Gilfillan's method for steel weight estimation, where the value of the steel factor is chosen as 0.032 as the best estimate, 0.029 as the optimistic estimate, and 0.035 as the pessimistic estimate. As shown in Fig. 15.5 the steel weight factor is ranked 1st in the merit order ranking and the last column shows that the percentage of the variance of the RFR which is accounted for by this variable is quite significant.

In actual practice, with the help of detailed knowledge the range of the variables will be more realistic than those considered in this thesis, therefore the merit ranking will change. For example the variation in the number of sets of containers has a significant influence on RFR. This variation is based on a theoretical model developed by Edmond and Wright (134), see Fig. 11.1, which shows that the Box/slot ratio is highly dependent on the box turnaround time. For a particular company the Box/slot ratio may have less variability and hence its significance on RFR will be less pronounced.
### Fig.I5.4. Output, Sensitivity Analysis, container capacity 1500 Teu and speed 18 Knots (Steel weight estimation method 4)

<table>
<thead>
<tr>
<th>VARIABLE NAME</th>
<th>BEST ESTIMATE</th>
<th>OPT. ESTIMATE</th>
<th>PESS. ESTIMATE</th>
<th>PERF. MEAS. AT OPT. EST.</th>
<th>PERF. MEAS. AT PESS. EST.</th>
<th>RANGE OF PERF. MEAS.</th>
<th>RANGE COEFF. OF VAP</th>
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<td>2.000</td>
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<td>57.019</td>
<td>8.815</td>
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<td>5000.000</td>
<td>7000.000</td>
<td>43.706</td>
<td>45.486</td>
<td>1.780</td>
<td>3.91</td>
</tr>
<tr>
<td>CLUCY'B</td>
<td>560.000</td>
<td>500.000</td>
<td>600.000</td>
<td>42.265</td>
<td>42.272</td>
<td>0.007</td>
<td>0.00</td>
</tr>
<tr>
<td>CLUCY'B</td>
<td>470.000</td>
<td>450.000</td>
<td>550.000</td>
<td>42.269</td>
<td>42.274</td>
<td>0.005</td>
<td>0.00</td>
</tr>
<tr>
<td>STEELF</td>
<td>0.052</td>
<td>0.029</td>
<td>0.035</td>
<td>44.195</td>
<td>44.196</td>
<td>0.000</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**VALUE OF KFR WHEN ALL VARIABLES EQUAL THEIR BEST ESTIMATES = 35.93**

**VALUE OF KFR WHEN ALL VARIABLES EQUAL THEIR OPTIMISTIC ESTIMATES = 22.96**

**VALUE OF KFR WHEN ALL VARIABLES EQUAL THEIR PESSIMISTIC ESTIMATE = 63.55**

**ESTIMATE OF MEAN OF KFR BASED ON PERT ESTIMATES OF THE MEANS OF VARIABLES = 36.46**

**ESTIMATE OF S.D. OF KFR BASED ON A S.D. TO RANGE RATIO OF 0.3 FOR THE VARIABLES = 3.45**
### Value of RFR When All Variables Equal Their Best Estimates = 30.41

### Value of RFR When All Variables Equal Their Optimistic Estimates = 18.47

### Value of RFR When All Variables Equal Their Pessimistic Estimate = 56.69

### Estimate of Mean of RFR Based on Pert Estimates of the Means of Variables = 30.84

### Estimate of S.D. of RFR Based on R.S.D. to Range Ratio of 0.3 for the Variables = 1.26
15.2. PROBABILISTIC APPROACH TO RISK ANALYSIS

'Pessimistic' and 'optimistic' estimates provide an indication of the uncertainty surrounding the best estimate made for a particular variable, but for a complete description of that uncertainty, a probability distribution is required. The probability distribution is a curve such that the area under the curve between two points is equal to the probability of the variable lying between those two points. One way of defining risk is by means of a probability distribution of Required Freight Rate and this is sometimes referred to as its 'risk profile'. Much of the work which has been carried out in the area of risk analysis has been concerned with deriving the 'risk profile' of the measure of merit.

A sensitivity analysis as pointed out earlier provides a useful first step in analysis of risk in capital investment. It involves using computer Model III to derive the mean and the standard deviation of the RFR and the merit ranking of variables in order of importance as contributors to the total risk. The next step is then the production of the risk profile for the capital investment.

The probabilistic approach to risk analysis can be subdivided into three broad categories,
(a) Analytical approach
(b) Other methods of Risk Analysis
(c) Monte Carlo Simulation.
Each of these methods are discussed in turn with more emphasis on Monte-Carlo simulation, which was chosen as the method to evaluate the risk in marine capital investment.

15.2.1. (a) Analytical approach

In the analytical approach the two most popular methods are,
(i) Hillier's Model (217)
(ii) Taylor Series Approach (211)

Hillier's model was developed in 1963 and modified further by Wagle (218) in 1967 and Zinn and Lesso (219) 1977.
The Hillier model is based on the properties of statistical
distribution, for derivation of the probability distribution
of two profitability criteria NPV and IRR from the estimated
mean and variance of the individual cash flows for each year.

Instead of producing a complete distribution of NPV
or IRR or the risk profile, it calculates only the mean and
the variance of NPV and IRR.

The major disadvantage of the Hillier Model is that it
cannot deal with types of cash flows generally encountered
in marine capital investment. The model deals only with
the sum of variables (205) and the calculation of the cash
flows in calculating the economic measure of merit in marine
investment generally involve products, non-linearities,
discontinuities, etc.

(ii) Taylor Series Approach

Taylor Series Approach has been successfully applied
to ship design by Wolfram (211) 1979. Wolfram argues that
the Taylor series approach is better than the Monte Carlo
approach since it can be carried out by hand calculation
compared to computer based Monte Carlo simulation. However
as the complexity of the problem to be formulated increases,
recourse to computer based Monte Carlo simulation becomes
necessary. This is because to formulate the ship design
problem analytically can be an arduous task.

(iii) Integral Transform Theory

The analytical approach based on Integral Transform
theory is one of the latest analytical techniques developed
since Hillier's model (217) in 1963. A complete exposition
of the technique can be found in Barnes (220) and is mentioned
here for completeness of the review.

Most of these above approaches depend on derivation of
highly mathematical and precise formulation of the probability
density function of the economic measure of merit. Such
preciseness is illusory since the cost data estimates on
which they operate are in most cases approximate values.
15.2.2 (b) Other methods of Risk Analysis

Each of the methods mentioned below are either extensions to already existing techniques or modifications to suit a particular type of problem.

(a) Parameter method, developed by Cooper and Davidson (216) 1976 is a simplification of the Monte Carlo simulation technique. The parameter method is so named because it deals with the parameters of the probability distributions involved rather than the distribution in their entirety. This method can easily be undertaken by a desk calculator. It assumes three values of the uncertain variables as in the computer Model III and for these variables the mean and variance is calculated assuming a triangular distribution. Knowledge of the two parameters, mean and variance of each uncertain variable then allows one to calculate the mean and variance of the economic measure of merit.

However it assumes that the probability density function of the economic measure of merit is a normal distribution and the uncertain variables are independent.

(b) Risk Analysis based on Risk Preference Theory (227). This technique forms an extension to the risk analysis by the Monte Carlo simulation technique. The 'risk profile' which is generated by the Monte Carlo simulation technique is used to calculate the 'certainty equivalent value'. The method incorporates the risk preference of the decision maker in a formal manner. Derivation of risk preference characteristics of a decision maker is based on subjective assessment. This method is mentioned here to complete the review. There are other methods which account for the probability of future cash flows and timing of these cash flows, one of these is given by Krappinger (228) for marine investment problems.

The advantages and disadvantages of the different techniques to evaluate the risk of an individual capital investment is given by Bonini (205) and some of these are summarised in Table 15.2.
<table>
<thead>
<tr>
<th>Description</th>
<th>Incorporation of various types of relationships</th>
<th>Time series relationship</th>
<th>Uncertainty about project life</th>
<th>Cash flow model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Certainty model 'best estimates'</td>
<td>Satisfactory as far as one number estimates go. Can have biases from non-linearities in relationships.</td>
<td>One point estimates only.</td>
<td>One point estimates only.</td>
<td>Monte Carlo Model</td>
</tr>
<tr>
<td>Sensitivity Analysis</td>
<td>Can be incorporated easily.</td>
<td>Included as covariances.</td>
<td>Included with some difficulty.</td>
<td>Taylor Series Approach</td>
</tr>
<tr>
<td>Hillier Model</td>
<td>Difficult to include all additive relationships. Subject to some discontinuities.</td>
<td>One point estimates only.</td>
<td>Not directly included.</td>
<td>Cash Flow model plus random samplings of unknown variables to estimate distribution of NPV</td>
</tr>
<tr>
<td>Analytical formula developed from sums to determine mean and variance of NPV</td>
<td>Can be incorporated but with some difficulty.</td>
<td>Easily incorporated.</td>
<td>Discrete discounting and discrete cash flows</td>
<td></td>
</tr>
<tr>
<td>Description</td>
<td>Certainty model</td>
<td>Hillier Model</td>
<td>Taylor Series Approach</td>
<td>Monte Carlo Model</td>
</tr>
<tr>
<td>-------------</td>
<td>----------------</td>
<td>--------------</td>
<td>------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td></td>
<td>One number 'best estimates' with Sensitivity Analysis</td>
<td>Analytical formula developed from sums of random variables to determine mean and variance of NPV</td>
<td>Hand calculation with calculator</td>
<td>Cash flow model plus random sampling from distributions of unknown variables to estimate distribution of NPV</td>
</tr>
<tr>
<td>Computational Requirements</td>
<td>Simple hand calculation with calculator</td>
<td>Hand calculation with calculator</td>
<td>Hand calculation with calculator</td>
<td>Computer program; but may be relatively inexpensive to build. Also computer package programs available.</td>
</tr>
<tr>
<td>(1) Simple model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2) Complex model</td>
<td>Simple calculations - may be programmed for computer if extensive sensitivity analysis desired.</td>
<td>Requires extensive calculations probably necessitating a computer program</td>
<td>Can be difficult to formulate the problem analytically.</td>
<td>Rather extensive computer program required. Since it is a sampling technique quite a large number of runs are required.</td>
</tr>
</tbody>
</table>
Monte Carlo simulation was first proposed by Hess and Quigley (207) in 1963 and made popular by Hertz (208, 209) in 1964, 1968, who also coined the word Risk analysis in his classical paper (208) in the Harvard Business Review. A complete description of the technique can be found in (204), (207), (208), (209), (210). The advantages and disadvantages of this technique can be found in (205), (211). Use of this technique in ship investment problems has been limited so far, but application in other industries can be found extensively in the literature, particularly in oil recovery projects (212), commerical manganese nodule mining (213) and the chemical industry. One of the earliest papers advocating this technique was by Klausner (204) 1970 for shipbuilding investments. Wolfram (211) in 1979 proposed an analytic approach. Application to container shipping problems have been mentioned by Webster in 1970 (210). Other references such as (214) by Woodward et al in 1968 mention use of the Monte Carlo technique for the strategy type of decision making such as in container allocation problems in container shipping.

The Monte Carlo simulation technique is outlined in Fig. 15.6. Each of these steps will be discussed in turn.

**Defining the Variables**

This initial step is the obvious starting point of any quantitative analysis: define the measure of merit, in this case RFR, and all the variables which affect it. These would include independent variables as well as the dependent variables. Initially the designer should not worry too much about dependency between variables, but dependencies are important and reference will be made later in the section on how to deal with them.

**Sorting the variables into Groups**

The variables identified in the previous step are sorted out into two groups. The first group consists of all the variables and parameters for which exact values are known. The second group includes all the variables and
Fig. 15.6. Monte Carlo Simulation Technique.

1. Define all variables
   Specify the measure of merit RFR, NPV or IRR and all the variables affecting it. The variables are described in terms of the probability density function.

2. Transform each of the probability-density functions into cumulative probability scale.

3. Generate random numbers uniformly distributed between 0 and 1, by a random number generator.

4. Sample for each variable, by setting equal to the numerically equivalent first set of different random numbers.

5. For each set of the random values of the uncertain variables, calculate the Required Freight Rate.

6. Store the results from each pass.

7. Compute the mean and standard deviation of the RFR for N passes.

8. Is the mean and standard deviation of RFR from the two separate streams of random numbers sufficiently close. If not, increase the number of passes.

9. Store the values of the RFR into frequency classes, and output the result as a histogram of probability distribution of RFR, or cumulative probability distribution, which is the risk profile of RFR.
parameters for which there is some uncertainty about their values. Most variables might fall into the second category but as pointed out earlier, only those variables, the change in which produces the maximum change in RFR, need be considered. In this case they amounted to 36 variables.

15.2.4. DEFINING DISTRIBUTIONS FOR THE UNKNOWN, RANDOM VARIABLES

This is the step where professional expertise and judgement of a designer is involved. This is one of the most important steps in the whole analyses. The final distribution of RFR will generally depend on the distribution of the variables that is: if all variables are independent and are represented by a normal distribution, then it is known from the central limit theorem (211) that the distribution of RFR will also be normal. The following guidelines should be observed when defining the distribution.

(a) The distribution can be of any shape, range or form. Standard statistical distributions such as normal and log normal may not be used. The distribution can be discrete or continuous. If variables are related to one another, the dependency relationship must be defined. (see Section 15.2.5).

(b) The judgement about the distribution need not be defined by a single person, but the expertise of the various staff knowledgeable about a variable may be consulted.

(c) The distribution can be assessed either objectively based on experimental data, nature of the variable or past historical record, or subjectively.

(d) If the opinions vary as to the nature, range, form, shape of the distribution then the various possible combinations can be tried for each complete run of the Monte Carlo analysis. As a result of such a sensitivity analysis, it may be found that the variable may not be critical.

In the program four types of distribution are found to be adequate to describe most of the variables. These distributions are listed in Table 15.3. Some writers (215) (4) (216) on simulation have taken the position that it is rare that values other than the minimum, most likely and the maximum of a variable are known at the preliminary design stages, therefore the triangular distribution can be used to describe the variables.
Table 15.3. Different types of distribution.

<table>
<thead>
<tr>
<th>Integer</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Variable is to be described in the simulation by a single estimate provided by the user.</td>
</tr>
<tr>
<td>2</td>
<td>Variable is to be described in the simulation by a PERT estimate of its mean which will be based on optimistic, pessimistic and best estimates provided by the user.</td>
</tr>
<tr>
<td>3</td>
<td>Variable is to be described in the simulation by a triangular distribution. The mean and standard deviation of the triangular distribution will be equal to the PERT estimates of the mean and standard deviation of the variable. These will be based on optimistic, pessimistic and best estimates provided by the user.</td>
</tr>
<tr>
<td>4</td>
<td>Variable is to be described in the simulation by a histogram which will be provided by the user as a pair of data values and the probability associated with such a value.</td>
</tr>
</tbody>
</table>
Indeed a uniform and triangular distribution would be adequate in most circumstances. The normal type of distribution for costs shown by Klausner (204) are difficult to estimate subjectively.

Some errors in defining triangular distributions

(a) Frequently there is an error in defining minimum and maximum. To illustrate the problem, suppose we have the following set of data of a random variable X:

10, 11, 12, 12, 12, 12, 16, 17, 19, 24

If this set of data is represented by a triangular distribution, then 10 is the minimum, 12 is the most likely and 24 is the maximum. The resulting triangular distribution would be as shown in Fig. 15.7.

But now suppose, instead, that the available data of the random variable X is:

10, 10, 10, 11, 11, 12, 12, 12, 12, 14, 17, 18, 20, 23, 24

Again 10 is the minimum value, 12 occurs most frequently and 24 is the maximum value and we may end up with a triangular distribution. These two sets of data are not the same, so we cannot represent both of them by the same triangular distribution. Thus a more rationale representation would be as shown in Fig. 15.8. The whole point to remember here is that when minimum and maximum value of a triangular distribution is mentioned, values for which the probability of occurrence vanishes to zero are implied as ranges closer and closer to the limits are considered.

(b) The best estimate is not necessarily the midpoint of the range of maximum or minimum but is the most probable value, which can be on either side of the range i.e. the triangular distribution need not be symmetrical.

(c) Triangular distribution generally give very poor representation of highly skewed data, see Fig. 15.9.
Fig. 15.7.

$f(x)$

Fig. 15.8.

$f(x)$

Fig. 15.9. Triangular distribution as an approximation to highly skewed distribution
15.2.5. DEALING WITH DEPENDENCIES

Two variables are dependent if a knowledge of the value of one of them would influence estimates made for the other. Suppose there are two variables "life of ship" and 'salvage value' of the ship and the best estimates for the ship's life is 20 years and for salvage value is zero. Now if the ship's life is changed to 15 years, will salvage value change, if the answer is yes, then the two variables are dependent. On the other hand if the estimate of salvage value remains unchanged then they are independent.

Dependencies cause problems in risk simulation because, when they are present, it is not correct to sample independently from the probability distribution of the different variables. Theoretically, the simulation should first sample from the distribution of the life of the ship and then, depending on the precise value obtained, choose an appropriate distribution for salvage value and sample from it.

The sensitivity analysis can, in many cases, be used to provide a rough indication of the effect of a dependence on the standard deviation of RFR. But it cannot be used to indicate the effect of the dependence on the mean of RFR or any other characteristic of the distribution of RFR (4).

One useful way of analysing dependencies is, to calculate (a) the distribution of RFR assuming no dependence; and (b) the distribution of RFR assuming total dependence.

Total dependence between two variables X and Y is defined as positive when X takes a value equal to its Kth fractile, Y also takes a value equal to its Kth fractile. X and Y are totally negatively dependent if X takes a value equal to its Kth fractile, Y takes a value equal to its (1-K)th fractile. When the independent distributions of X and Y happen to be of the same shape then total dependence, implies that the coefficient of correlation ρ is +1 or -1. This is what is taken in this program, i.e. either total positive dependence or total negative dependence.

A brief review of other more sophisticated ways to deal with dependencies is given by Hull (4).
15.3. APPLICATION OF RISK ANALYSIS TO CAPITAL INVESTMENT

The Monte Carlo simulation was used to derive the probability density function of the risk profile of RFR. The various subroutine subprograms developed in this section can also be used for other ship types. The Computer Model IV is used to generate the risk profile curve of the RFR. The program structure, input and output of the subroutines are discussed and the computer model IV is used to show its applicability in certain situations. The discussion is mainly about capital investment in containership, but is equally applicable to other ship types.

15.3.1. COMPUTER ALGORITHMS

Generally well developed and tested, general purpose algorithms for carrying out Monte Carlo simulation are available. Berger (221) and Fliescher and Lubin (222) give information about these various program packages. Based on this information various sources were contacted. Many of these program packages are highly sophisticated and therefore expensive to acquire and implement. Therefore three general purpose algorithms were selected because of their low cost and these are given below.

a) GRASP (222). Generalized Risk Analysis Package developed by Department of Industrial Engineering, Iowa State University. The programs were in PL/I, which meant it had to be rewritten in FORTRAN and therefore was not accepted. It is well documented and inexpensive.

b) ERRCAL (224). A general purpose Monte Carlo program. The source program is in FORTRAN, and was developed for CDC 6600. This package could not be implemented on the ICL 2976 with the VME/B operating system because the source program is not well documented and therefore the program logic was difficult to unscramble for errors during compilation.

c) UPFAR (225). A Utility Program For the Analysis of Risk. This package could not be acquired because copyrights had not been
established. This program uses Risk Preference Theory to
generate the risk profile curve based on the utility function
of the decision maker, and if available in future could form
an extension to the computer algorithm developed in this
thesis.

A literature survey revealed two algorithms to carry
out the Monte Carlo simulation. These were:

1) PLADE (226). This suite of programs is the most
comprehensive package found to carry out Risk analysis, both
for situations where a single accept/reject decision have
to be made and others where sequential investment decisions
have to be made. That is situations where several decisions
on an investment have to be made over a period of time
such as the strategy type of decision making in container
allocation problems in container shipping as given by
Woodward et al. (214). This program is well documented
but will need certain modifications before it can be applied
for marine capital investment.

2) RISKANAL2 (4) This suite of program is well suited to
the accept/reject type of decisions usually made in marine
capital investment. It needed fairly little modification
and was therefore implemented on the ICL 2976 with VME/B
operating system at Glasgow University.

15.3.2. PROGRAM STRUCTURE AND INPUT/OUTPUT

The overall program structure of Computer Model IV
which carries out the Risk Analysis is shown in Fig. 15.10.
The main program of computer Model II was modified to input
data values of the distribution of the uncertain variables.
The user can assign four types of distribution for the
uncertain variables as shown in Table 15.3. The thirty six
variables chosen in Section 15.1.3. were also used for
carrying out the Risk analysis.

The functions of the various subroutines are well
documented by Hull (4) 1980. Some of these subroutines
needed minor modifications, others which were developed for
Fig. 15.10. Program structure, probabilistic phase to carry out risk analysis and generation of risk profile. (Computer Model IV).

Main program
Read in data for
ship characteristics
and other data
values for risk
analysis
(9941)

Subroutine
Triang
(308)

Subroutine
GRAPHP
(428)

Subroutine
CONTLR
(N, NC, X, G)
(5336)

Subroutine
COLECT
(182)

Subroutine
COPY
(764)

Subroutine
GRPLOT
(2314)

Subroutine
SIM
(1210)

Subroutine
HEADIN
(816)

Subroutine
RANDOM
(122)

Subroutine
SAMPLE
(680)

Subroutine
SENPAR
(476)

Subroutine
FUNCTN
(3298)

Subroutine
CONSTR
(3222)

Call to
standard
NAG library
for random
numbers
GØ5CCF
GØ5CAF

(Note. Figures in the bracket indicates the program size excluding common statements, Total = 146K).
this thesis are mentioned briefly.

RANDOM - This subroutine is used to generate pseudorandom numbers from 0-1 and is uniformly distributed. This subroutine depends on the type of computer used and the source program is in machine language. Standard NAg (Numerical Algorithm Group) subroutine was used.

SENPAR - This subroutine is the same as developed for Computer Model III.

FUNCTN & CONSTR - This subroutine is the same as developed for Computer Model II.

COPY - This subroutine is used for copying K characters from array A to array B starting at the Ith character in A and Jth character in B.

Subroutines which calculate the costs, weights and other design and economic values are as developed in Computer Model I.

A sample input data for carrying out a Risk analysis with Computer Model IV is shown in Fig. 15.11.

The input data values are similar to the one given in Computer Model III Fig. 15.2 except that the type of distribution is associated with each of the thirty six variables.

Simulation analysis by Monte Carlo technique usually takes a lot of computer time, therefore the minimum number of simulation runs to be made had to be determined. An analysis of the number of runs as shown below, indicates that no improvement in the value of standard deviation or the mean of Required Freight Rate is obtained after 4000 simulation runs.

Unfortunately there are no prescribed rules to tell exactly how many passes are required (215). In the absence of a rule the above method is the usual practice.
SIMULATION OF 2250 TEU CONTAINER SHIP 18 KNOTS SPEED

INPUT VALUES AS READ IN THE DATA FILE

SIMULATION OF 2250 TEU CONTAINER SHIP 18 KNOTS SPEED
2250.000CNT 18.000V 33.83.0EUDUR 6.766.0011T 1.0PORTF 1.0PORTD
4NCLPH 0.000BALST 0.03 3PRBP
9.0USAWS 10.0FSRS 11.0OISIER 13.0FTIER 0.550SGB 0.700FCB 10.0DROWS 13.0TIERS
10.0D/DMINT14.50L/DMAX 0.400V/L 1.500V/L 6.000/L 9.000/L 2.258/T 3.758/T
120.0REVSRIN18REV/LDUALAS 11PMPC 0IPRINT 21STEEL
0.05ACONT 0.05ARMANT 0.05ACINS
0.05MAGNES 0.05CREW 0.05PROV 0.05STORE
0.05APIINS 0.05ADMINS 0.05ARMANT
0.05APORT 0.05FUEL 0.05HANDEL

SN 22MC 36MVAR
273.775LENGTH 32.165BREADHT 10.125DRAFT 24.197DEPTH 0.657BLOCK COEFF.
40000RUN ONDEP
3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 2 2 2 2 TYPE OF DISTRIBUTION

OVHEAD 3 100.000 90.000 220.000
WR 3 2.400 2.000 3.000
S1COS 3 214.000 200.000 250.000
SINDEX 3 169.300 150.000 200.000
PROFIT 3 15.000 10.000 20.000
CHANDL 3 50.000 40.000 60.000
CLSCY 3 560.000 500.000 600.000
CLSCY 3 470.000 400.000 500.000
CREDL 3 145.000 125.000 180.000
COFUEL 3 80.000 60.000 180.000
WOFF 3 8400.000 8000.000 10000.000
WPO 3 5400.000 5000.000 7000.000
WCWR 3 5300.000 5000.000 6000.000
PCINT 3 12.000 10.000 15.000
YLOAD 2 7.000 8.000 9.000
STEEL 2 0.05 0.029 0.035
QFFIT 2 0.320 0.300 0.340
SLIFE 3 20.000 15.000 25.000
DISCMT 3 15.000 12.000 18.000
ALPH 3 0.850 0.750 0.900
ALF 3 0.850 0.700 0.850
CLIFE 3 8.000 6.000 10.000
SETCNT 3 2.500 1.800 3.000
CPINT 3 10.000 9.000 12.000
COSMIN 3 2500.000 2250.000 3000.000
PCFD 3 2.700 1.500 3.300
PCFF 3 2.100 1.500 3.300
PECFD 3 7.600 3.600 11.600
PECFF 3 9.600 3.600 11.600
RLAB 3 0.390 0.280 0.500
RLADB 3 0.600 0.500 0.920
OFF 2 12.000 10.000 15.000
PO 2 6.000 6.000 8.000
CREW 2 20.000 18.000 24.000
TAXCT 3 52.000 50.000 55.000
DELAY 2 1.000 0.000 2.000

Fig.5.II. Input data, Risk Analysis, container capacity 2250 Teu and speed 18 knots.
Table A. 2250 Teu Ship and speed = 18 knots.

<table>
<thead>
<tr>
<th>No. of Simulation Runs</th>
<th>Computer Time in secs.</th>
<th>Required Freight Rate £/tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean Standard deviation</td>
</tr>
<tr>
<td>500</td>
<td>116</td>
<td>38.627 3.203</td>
</tr>
<tr>
<td>1000</td>
<td>216</td>
<td>38.292 3.158</td>
</tr>
<tr>
<td>2000</td>
<td>408</td>
<td>38.054 3.079</td>
</tr>
<tr>
<td>4000</td>
<td>794</td>
<td>38.086 3.481</td>
</tr>
<tr>
<td>6000</td>
<td>1193</td>
<td>37.930 3.428</td>
</tr>
<tr>
<td>7000</td>
<td>1382</td>
<td>37.936 3.561</td>
</tr>
</tbody>
</table>

15.3.3. REQUIRED FREIGHT RATE ASSUMING NO DEPENDENCIES

Containerships of 1500 Teu and 2250 Teu both with a speed of 18 Knots were selected for assessing the risk involved in these two investment decisions. Fig. 5.13 shows the risk profile or the probability distribution of RFR for the 1500 Teu ship and Fig. 15.12 shows the probability distribution of RFR of the 2250 Teu ship. The results are tabulated below.

Table B.

<table>
<thead>
<tr>
<th>£/tonne</th>
<th>1500 Teu</th>
<th>2250 Teu</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFR, computer Model II</td>
<td>35.93</td>
<td>38.310</td>
</tr>
<tr>
<td>Mean RFR, computer Model III</td>
<td>36.46</td>
<td>38.880</td>
</tr>
<tr>
<td>Mean RFR, computer Model IV</td>
<td>35.713</td>
<td>38.136</td>
</tr>
<tr>
<td>Std. dev., computer Model III</td>
<td>3.45</td>
<td>3.73</td>
</tr>
<tr>
<td>Std. dev., computer Model IV</td>
<td>3.060</td>
<td>3.317</td>
</tr>
</tbody>
</table>

For the 1500 Teu and 2000 Teu ship the value of RFR calculated by computer Model IV is less than those calculated by computer models III and II. And the value of RFR calculated by computer model II is the lowest as would be expected when the best estimates are made.
Fig. I5.2. Output, Risk profile, container capacity 2250 Teu and speed 18 Knots

**DISTRIBUTION OF REQUIRED FREIGHT RATE**
**NO DEPENDENCIES ASSUMED**

**MEAN** = 38.136  **S.D.** = 3.317

<table>
<thead>
<tr>
<th>RANGE</th>
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</tr>
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<tbody>
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</tr>
<tr>
<td>25.5 TO</td>
<td>0.0000</td>
</tr>
<tr>
<td>26.0 TO</td>
<td>0.0000</td>
</tr>
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<td>26.5 TO</td>
<td>0.0000</td>
</tr>
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<td>27.0 TO</td>
<td>0.0000</td>
</tr>
<tr>
<td>27.5 TO</td>
<td>0.0000</td>
</tr>
<tr>
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</tr>
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<tr>
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</tr>
<tr>
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<td>0.0110</td>
</tr>
<tr>
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<td>0.0173</td>
</tr>
<tr>
<td>33.0 TO</td>
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</tr>
<tr>
<td>33.5 TO</td>
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</tr>
<tr>
<td>34.0 TO</td>
<td>0.0330</td>
</tr>
<tr>
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<td>0.0428</td>
</tr>
<tr>
<td>36.0 TO</td>
<td>0.0560</td>
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<td>0.0618</td>
</tr>
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<td>37.5 TO</td>
<td>0.0745</td>
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<td>0.0230</td>
</tr>
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<td>0.0220</td>
</tr>
<tr>
<td>43.0 TO</td>
<td>0.0133</td>
</tr>
<tr>
<td>43.5 TO</td>
<td>0.0135</td>
</tr>
<tr>
<td>44.0 TO</td>
<td>0.0080</td>
</tr>
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<td>44.5 TO</td>
<td>0.0082</td>
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<td>0.0047</td>
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</tr>
<tr>
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<td>0.0007</td>
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<td>48.0 TO</td>
<td>0.0007</td>
</tr>
<tr>
<td>48.5 TO</td>
<td>0.0000</td>
</tr>
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<td>0.0007</td>
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<td>50.0 TO</td>
<td>0.0000</td>
</tr>
<tr>
<td>50.5 TO</td>
<td>0.0000</td>
</tr>
<tr>
<td>51.0 TO</td>
<td>0.0002</td>
</tr>
<tr>
<td>GREATER THAN</td>
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</tr>
</tbody>
</table>
Fig. I5.13. Output, Risk profile, container capacity 1500 Teu and speed 18 Knots.

**DISTRIBUTION OF REQUIRED FREIGHT RATE NO DEPENDENCIES ASSUMED**

**MEAN = 35.713  S.D. = 3.060**

<table>
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<th>RANGE</th>
<th>PROB</th>
</tr>
</thead>
<tbody>
<tr>
<td>LESS THAN</td>
<td></td>
</tr>
<tr>
<td>24.0 TO</td>
<td>0.000</td>
</tr>
<tr>
<td>24.5 TO</td>
<td>0.000</td>
</tr>
<tr>
<td>25.0 TO</td>
<td>0.000</td>
</tr>
<tr>
<td>25.5 TO</td>
<td>0.000</td>
</tr>
<tr>
<td>26.0 TO</td>
<td>0.000</td>
</tr>
<tr>
<td>26.5 TO</td>
<td>0.000</td>
</tr>
<tr>
<td>27.0 TO</td>
<td>0.000</td>
</tr>
<tr>
<td>27.5 TO</td>
<td>0.013</td>
</tr>
<tr>
<td>28.0 TO</td>
<td>0.013</td>
</tr>
<tr>
<td>28.5 TO</td>
<td>0.018</td>
</tr>
<tr>
<td>29.0 TO</td>
<td>0.047</td>
</tr>
<tr>
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<td>0.050</td>
</tr>
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<tr>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>33.0 TO</td>
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<tr>
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</tr>
<tr>
<td>40.5 TO</td>
<td>0.018</td>
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<tr>
<td>41.0 TO</td>
<td>0.013</td>
</tr>
<tr>
<td>41.5 TO</td>
<td>0.011</td>
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</tr>
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<td>42.5 TO</td>
<td>0.007</td>
</tr>
<tr>
<td>43.0 TO</td>
<td>0.005</td>
</tr>
<tr>
<td>43.5 TO</td>
<td>0.018</td>
</tr>
<tr>
<td>44.0 TO</td>
<td>0.023</td>
</tr>
<tr>
<td>44.5 TO</td>
<td>0.010</td>
</tr>
<tr>
<td>45.0 TO</td>
<td>0.005</td>
</tr>
<tr>
<td>45.5 TO</td>
<td>0.010</td>
</tr>
<tr>
<td>46.0 TO</td>
<td>0.000</td>
</tr>
<tr>
<td>46.5 TO</td>
<td>0.000</td>
</tr>
<tr>
<td>47.0 TO</td>
<td>0.000</td>
</tr>
</tbody>
</table>

GREATER THAN

446
However uncertainty surrounding the variables have less pronounced effect on RFR of a 1500 Teu ship compared to a 2250 Teu ship. The standard deviations calculated by both the computer Models III and IV are in good agreement. This indicates that computer Model III gives a fairly good approximation to the total risk.

Table C. RFR for 4000 simulation runs (RFR in £/tonne)

<table>
<thead>
<tr>
<th>Speed (knots)</th>
<th>µRFR</th>
<th>σRFR</th>
<th>Value of RFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>35929</td>
<td>3174</td>
<td>35700</td>
</tr>
<tr>
<td>21</td>
<td>36707</td>
<td>3122</td>
<td>36600</td>
</tr>
<tr>
<td>24</td>
<td>39540</td>
<td>3286</td>
<td>39580</td>
</tr>
<tr>
<td>27</td>
<td>45.841</td>
<td>3.901</td>
<td>45.750</td>
</tr>
</tbody>
</table>

Further an analysis with increasing speed showed that the expected value of RFR, $µ_{RFR}$, in the probabilistic phase is similar to the one calculated in the deterministic phase. Therefore for a 1500 Teu ship the deterministic phase with Computer Model II may be adequate. And a rough measure of total risk can be obtained from Computer Model III.

Change in distribution

The user can also carry out a sensitivity analysis with the probabilistic approach. For a ship of 1500 Teu, 18 Knots the first six variables in the input list (Fig. 15.11) were assigned uniform rectangular distribution instead of a triangular distribution. The results are as shown below.

Table D. Values of mean RFR and standard deviation. (RFR in £/tonne)

<table>
<thead>
<tr>
<th>Distribution</th>
<th>µRFR</th>
<th>σRFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variables with Distribution as shown in Fig. 15.11</td>
<td>35.929</td>
<td>3.174</td>
</tr>
<tr>
<td>First six variables changed to a rectangular uniform distribution, Type 2</td>
<td>36.561</td>
<td>2.676</td>
</tr>
</tbody>
</table>
The above Table D shows that changing the distribution of certain variables has some influence on the $\mu_{\text{RFR}}$ and $\sigma_{\text{RFR}}$. Such a sensitivity analysis can be carried out for change in distribution of other variables to ascertain whether the probability distribution representing the uncertainty surrounding these variables can be neglected or can be replaced by a simpler distribution. Finally a cumulative probability curve, shown in Fig. 15.15 is drawn from the probability histogram Fig. 15.13. This shows that there is a 54.5% chance that the Required Freight Rate will be less than the expected RFR, $\mu_{\text{RFR}}$ of £35.713/tonne. Conversely there is a 45.5% chance that the RFR will exceed this value. Also the range of probable value of RFR is relatively narrow (Fig. 15.13). Similarly the cumulative probability curve for a containership of 2250 Teu at 18 knots speed was derived from Fig. 15.12 and shown in Fig. 15.15. The expected Required Freight Rate for this ship is £38136/tonne and the cumulative distribution shows that there is 52.5% chance that the RFR will be less than the $\mu_{\text{RFR}}$.

However as the curves show, capital investment in the 2250 Teu ship is less risky, than the investment in the 1500 Teu ship and there is a slightly greater chance of achieving the expected RFR of £38136/tonne in the case of the 2250 Teu ship. At their respective level of expected RFR the Risk involved in case of both ships are similar as indicated by the area under the curve.

15.3.4. REQUIRED FREIGHT RATE ASSUMING DEPENDENCIES

The Computer Model IV in the last section was used for evaluation of Risk assuming that all the variables were independent. Dependencies can be tested by Computer Model IV. The following dependencies were checked.

(a) positive dependence between shipbuilding labour wage rate and overheads and is shown in Fig. 15.14.
(b) positive dependence between Inbound and Outbound Load factor.
(c) positive dependence between steel cost and overheads.
Fig. I5.I4. Output Risk profile, container capacity 1500 Teu and speed 18 Knots (Assuming dependency)

<table>
<thead>
<tr>
<th>Ovhead</th>
<th>Assumed to be positively dependent on ( W )</th>
</tr>
</thead>
<tbody>
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<td>Prob</td>
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</tr>
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<td>24.5 to 25.0</td>
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</tr>
<tr>
<td>25.0 to 25.5</td>
<td>0.0005</td>
</tr>
<tr>
<td>25.5 to 26.5</td>
<td>0.0005</td>
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<td>0.0040</td>
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</tr>
<tr>
<td>29.0 to 29.5</td>
<td>0.0048</td>
</tr>
<tr>
<td>29.5 to 30.0</td>
<td>0.0048</td>
</tr>
<tr>
<td>30.0 to 30.5</td>
<td>0.0140</td>
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<td>0.0122</td>
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<td>31.0 to 31.5</td>
<td>0.0140</td>
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<tr>
<td>31.5 to 32.0</td>
<td>0.0220</td>
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<tr>
<td>32.0 to 32.5</td>
<td>0.0288</td>
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<tr>
<td>32.5 to 33.0</td>
<td>0.0350</td>
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<tr>
<td>33.0 to 33.5</td>
<td>0.0388</td>
</tr>
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<td>33.5 to 34.0</td>
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<td>36.0 to 36.5</td>
<td>0.0684</td>
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<tr>
<td>36.5 to 37.0</td>
<td>0.0744</td>
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<tr>
<td>37.0 to 37.5</td>
<td>0.0800</td>
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<tr>
<td>37.5 to 38.0</td>
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<td>38.5 to 39.0</td>
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<td>0.1500</td>
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<td>42.0 to 42.5</td>
<td>0.0786</td>
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<td>0.0048</td>
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</tr>
<tr>
<td>44.0 to 44.5</td>
<td>0.0020</td>
</tr>
<tr>
<td>44.5 to 45.0</td>
<td>0.0016</td>
</tr>
<tr>
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</tr>
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<td>46.5 to 47.0</td>
<td>0.0000</td>
</tr>
<tr>
<td>Greater than 47.0</td>
<td>0.0000</td>
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</table>

MEAN = 34.113, S.D. = 3.787
1500 Teu ship, 18 knots, 2500 runs.

<table>
<thead>
<tr>
<th>Dependency</th>
<th>RFR\textsubscript{1}</th>
<th>£/tonne</th>
<th>(\mu_{RFR})</th>
<th>(\sigma_{RFR})</th>
</tr>
</thead>
<tbody>
<tr>
<td>No dependency</td>
<td></td>
<td>£/tonne</td>
<td>35.684</td>
<td>2.927</td>
</tr>
<tr>
<td>Dependency (a)</td>
<td>RFR\textsubscript{2}</td>
<td>£/tonne</td>
<td>36.113</td>
<td>3.052</td>
</tr>
<tr>
<td>Dependency (b)</td>
<td>RFR\textsubscript{3}</td>
<td>£/tonne</td>
<td>35.738</td>
<td>2.987</td>
</tr>
<tr>
<td>Dependency (c)</td>
<td>RFR\textsubscript{4}</td>
<td>£/tonne</td>
<td>35.671</td>
<td>2.856</td>
</tr>
</tbody>
</table>

The only two dependencies which showed any significant effect on the mean and standard deviation of RFR\textsubscript{1} are the positive dependency between labour wage rate and overhead and that between the load factors. Unit cost of steel has no significant effect on overhead, showing that this dependency can be neglected and each of them sampled from a different distribution.

Therefore dependencies between any two variables can be ascertained with the use of Computer Model IV.
CHAPTER 16

DISCUSSION, CONCLUSION AND FUTURE DEVELOPMENTS
16.1. GENERAL

The application of the digital computer to ship design and operation has created many preliminary design and operation programs over the past two decades. Since the use of such programs is still not commonplace when preliminary design is being carried out further improvement and development of these programs is required. This thesis describes a digital computer model for the preliminary design and operation of cellular containerships which offer the user four modes of operation to be used individually or in sequence. The last mode produces a risk profile for the design.

16.2. DISCUSSION

A complete overview of the computer aided containership design at the preliminary design stage as incorporated in this thesis is shown in Fig. 16.1.

It was not difficult to build the logic of the computer programs to carry out preliminary design studies. Most of the effort involved matching the various subprograms to give reasonable results within an acceptable range of ship size and speed. Although some of the subprograms were available to carry out certain design calculations, they had to be rewritten to suit the requirements and range acceptable for containership studies.

There were two types of facilities available, as shown in Fig. 16.1, for submission of work to the computer. One was the batch mode through job control cards, the other was the batch mode through a terminal. The submission of jobs through a terminal was preferred in most cases. It allowed the user a limited amount of interactive facility. One of the major attractions of using the terminal mode of computing was that in most instances the running of the program could be interrupted. This suppressed unnecessary amounts of output which might be generated. Secondly in many instances the automated decision logic or path embedded in the programs could be changed or overridden.
Fig. 16.1. A complete overview of the computer aided design procedure.

<table>
<thead>
<tr>
<th>Deterministic Phase</th>
<th>Computer Type of Computer Model</th>
<th>Type of mode possible</th>
<th>Type of mode preferable</th>
<th>Computer time including compilation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Parametric variation of principal dimensions of large number of designs and location of optimum design manually. May be possible to automate the search procedure by simple sorting routines.</td>
<td>1</td>
<td>1</td>
<td>1500 secs for three ( C_b ) values in steps of 0.01</td>
</tr>
<tr>
<td>II</td>
<td>Optimisation Technique for locating the optimum design.</td>
<td>1 or 2</td>
<td>2</td>
<td>200 secs for three ( C_b ) values in steps of 0.01</td>
</tr>
<tr>
<td>I</td>
<td>Sensitivity analysis</td>
<td>1 or 2</td>
<td>2</td>
<td>18 secs for variation in only one value</td>
</tr>
<tr>
<td>II</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Probabilistic Phase</th>
<th>Computer Type of Computer Model</th>
<th>Type of mode possible</th>
<th>Type of mode preferable</th>
<th>Computer time including compilation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>III</td>
<td>Sensitivity analysis with an approximation to total risk of the project</td>
<td>1 or 2</td>
<td>2</td>
<td>25 secs for one ship</td>
</tr>
<tr>
<td>IV</td>
<td>Generation of Risk Profile of Required Freight Rate</td>
<td>1 or 2</td>
<td>2</td>
<td>4000 simulation runs, 1500 secs. Initial interactive 100 simulation runs</td>
</tr>
</tbody>
</table>

Notes: 1 = Batch mode with submission of work through job control cards.
2 = Batch mode with submission of work through a terminal, with limited interactive facility and output on a VDU.

Computer used: - ICL 2976, with VME/B operating system.
More than a decade has gone by since the containership was introduced but it is still difficult for many to understand that the 'container capacity' expressed solely as TEU's does not adequately identify the size of the vessel. It was shown that for a given value of average weight of each container, operational metacentric height and container stowing procedure the designer can determine the container capacity and the associated draft. Therefore containerships should be compared for their carrying ability, only when these other factors have been defined.

One of the factors which reduces the acceptability of preliminary design programs are the large number of empirical relationships used to estimate the design parameters. These empirical relationships need to be improved especially for weight, centre of gravity and cost estimation. It was found that steel weight had a significant influence on the Required Freight Rate so emphasising the need for better expressions for steelweight and centre of gravity.

Any investment decision is concerned with a choice among alternatives, and it is always subject to an unknown future environment. An investment policy, if it is to guide management's choices among investment alternatives must embody two components both incorporated in this thesis. There were:

(a) An economic criteria by which to measure the relative economic attributes of investment alternatives.
(b) Decision rules, which make use of Risk analysis or otherwise seek to force uncertainty into account for selecting an acceptable investment.

The first component, economic criteria have been the subject of much analysis and discussion. On the other hand, the second component, the rules for making choices, particularly under uncertainty, have been given less attention in the past. It was shown how this could be incorporated and the risk profile of the investment generated. Of course no pre-established decision policy can take into account all considerations, human, organisational, strategic and financial that typically enter into any major capital investment decision. In this thesis, however, we are concerned with the question of financial policy which does lend itself to be formulated.
quantitatively.

Such a risk analysis based policy then specifies how management would prefer to attain a particular value of Required Freight Rate. The risk analysis model (computer model IV) also acts as a tool for testing and analysing past and future capital investment decisions. The management can analyse its own past investment data by generation of a risk profile and determine whether the past decisions have been consistent. If not, a more consistent decision policy can be formulated.

The probabilistic approach was designed with two key observations about risk simulation in mind. 

(a) A major reason why risk simulation has not been widely accepted in marine capital investment is because of the large number of probability assessments which a designer or user is typically required to make to undertake such a risk analysis.

(b) The cost of computer time used to carry out a risk simulation can be significant.

Therefore the essence of the approach adopted in this thesis was that assessments are only made at the probabilistic stage for variables which show significant influence on RFR at the deterministic stage. One significant advantage of subdividing the design process into the two stages, that is deterministic and probabilistic, was that it obviates the need to expend unnecessary effort in getting better estimates of the variables which have been found to have little or no influence on Required Freight Rate in the previous stage. The difficulty of assigning probability distribution to variables was overcome by assuming simpler distributions. A number of risk analyses showed that it is not wasteful in terms of computing cost since such analyses will be necessary for one or two competing cases only. This approach is outlined in Fig. 16.2.
Sensitivity analysis in the deterministic stage and identification of major influencing variables

User provides optimistic, pessimistic and most likely estimates for each variable found to have significant influence on RFR in the previous stage.

Sensitivity analysis carried out in the probabilistic stage with these values to evaluate the contribution of each variable to the total risk.

Risk simulation carried out on the basis of assessment made so far

Is the investment acceptable on the basis of the distribution of RFR obtained so far

Y → Investment accepted

N

Could the investment become acceptable if more assessments are made

N → Investment not accepted

Y

Make more assessment studies such as check on dependencies and change of distribution
Finally it has been shown in this thesis that a computer aided preliminary containership design program should incorporate uncertainties since influence of some parameters to overall risk can be significant. Explicit consideration of risk inherent in a project must form a part of the preliminary design programs.

16.3. CONCLUSIONS

(1) On the North Atlantic Route, for two ports of call a ship of container capacity 1500 teu to 1750 teu and speed of 16 to 18 knots gives a lower Required Freight Rate compared to other ship sizes and speeds.

(2) Sensitivity analysis based on a probabilistic approach gives a better measure for ranking of the variables.

(3) A sensitivity analysis based on a probabilistic approach may be adequate in some circumstances to assess the total risk of the capital decision.

(4) The preliminary design procedure should incorporate risk analysis to evolve a more consistent decision making policy for capital investments.

(5) The preliminary design procedure should be subdivided into various stages, which allow one to identify the important variables and their influence on the RFR. This obviates the need to expend effort in getting better estimates of the variables which have been found to have little or no significance on the RFR in the previous stage of the design.

16.4. FUTURE DEVELOPMENT

Results from programs must be as accurate as possible and such accuracy demands a long period of tuning of the program to ensure that the many internal relationships both scientific and empirical are as accurate as possible. An extension to this type of tuning is the replacement of simple empirical relationships by more complex scientific ones. In particular this is required for the subroutines concerned with
structural design, seakeeping and service performance. Sensitivity analysis may be used to choose areas worthy of improvement but the cost and the possibility of improvement must also be considered.

The Required Freight Rate must be established per Teu as well as per tonne enabling a wider range of studies to be carried out and ballasting considered in detail.

The maintenance effort required to update a program even without major changes must be carefully allowed when considering the future.

Although interactive computing takes up a great deal of terminal time it allows the experience of the user to be applied more readily and the program needs to be adjusted to permit more interaction. Graphical output is also useful to supplant and to supplement numerical output.

A containership can be viewed as one link in a door to door transport chain. Optimising this link may not be of benefit to the whole chain and an extension of the program to door to door container transport would be valuable. Other competitive modes of transport cannot be ignored and need their own computer programs.

In its present form the program needs modification to apply to fleets of containerships. However many of the subroutines can be applied by themselves in separate sea transport studies, especially those concerned with resistance and propulsion and finance.

The Required Freight Rate ignores income and it may be worth considering how to incorporate numerical routines to gauge the benefit of attracting more income.
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APPENDIX I

FLOW CHART FOR CALCULATION OF EFFECTIVE HORSEPOWER

READ IN
SPEED, LENGTH B.P., BREADTH MLD, DRAFT DESIGN, BLOCK COEFFICIENT

CIRCULAR DATA STORED AS AN ARRAY FOR BLOCK COEFFICIENTS OF 0.52 TO 0.72 INTERVALS OF 0.02 AND SPEED-LENGTH RATIO \( \sqrt{v/L} \) FROM 0.40 TO 1.15 INTERVALS OF 0.05

\[
N \quad 0.48 \leq CB \leq 0.72 
\]

\[
N \quad 0.40 \leq \sqrt{v/L} \leq 1.5 
\]

INTERPOLATE FOR REQD. CB
INTERPOLATE FOR REQD. \( \sqrt{v/L} \)

CORRECTION FOR BEAM AND DRAFT USING MUMFORD'S INDICES

BEAM CORRECTION
\[
CIRC1 = CIRCM \times (400.0 \times B/(L \times 55.0))^{0.2333} 
\]

\[
\nu^{2/3} = 0.447 \times \sqrt{v/L} - 3.606 
\]

DRAFT CORRECTION
\[
CIRC2 = CIRC1 \times (400.0 \times T/(L \times 18.0))^{p} 
\]

\[
100 \leq L \leq 400 
\]

\[
OL = FUNC1(L), \quad OL = FUNC2(L) 
\]

\[
OCORR = OL - 0.0741 
\]

\[
CIRL = 1.055 \times \sqrt{v/L} 
\]

\[
CIRCS = 0.0935 \times (1.7 \times L \times T + CB \times L \times B)/(L \times B \times T \times CB/35.0) \times 0.666 
\]

SKIN FRICTION CORRECTION
\[
SFC = OCORR \times CIRCS/(CIRL^{0.175}) 
\]

\[
CIRC = CIRC2 + SFC 
\]

\[
EHP = CIRC^{*}(v^{3.0})*((L*B*T*CB/35.0)^{0.667})/427.1 
\]

RETURN

END
CALCULATION OF SHAFT HORSE POWER AND CHOICE OF PROPELLER

READ

V=SPEED, AL=LENGTH B.P., B=BEAM, T=DRAFT, CB=BLOCK COEFF, EHP=EFFECTIVE HP NAKED HULL, REVSIN=RPM OF PROPELLER, IREVLD=TRIGGER FOR CHANGE IN RPM TO IMPROVE EFFY

VL = V/SQRT(AL)
IREVLD = 2
REVS = REVSIN
PRPDIA = 0.70 * T

IF PRPDIA > 28.0

EHPN = EHP
WEAIRA = 1.075 + 0.1667*V/\sqrt{L}
BAR = 0.60

CONTINUE

PFBNEW = 0.1

SHP = 1.5 * EHPN

IF NO PROP = 1

NO PROP = 1

CF = 0.367 + 2.50/(L**0.25) + 27.5/L
CF = 1.07 - 0.002*L

EHPT = EHPN*CF
EHPS = EHPT*WEAIRA
SHP = SHP/WEAIRA

IF NOPROP = 2

NOPROP = 2

Cw = 1.0/3.0 + 2.0*CB/3.0
CM = 0.06*CB + 0.94
W1 = 4.5*B*(CB**2.0)/(AL*CW*CM)
W2 = (7.0 - 6.0*CB/CW)*(2.8 - 1.8*CB/CM)
W3 = 0.5*(PRPDIA*0.625/T - 0.0873 - PRPDIA/B
WAKE = 0.1 + W1/W2 + W3
THRDED = WAKE*(0.5 + 0.4*(VL-0.5))
RRE = 1.02
\[ WAKE = 2 \cdot CB^5 \cdot 0.5 \cdot (1.0 - CB) + 0.2 \cdot 0.866^2 - 0.02 \]
\[ \text{THRDED} = 0.25 \cdot WAKE + 0.14 \]
\[ \text{RRE} = 0.985 \]
\[ \text{SPDADV} = V \cdot (1.0 - WAKE) \]
\[ \text{HULEFF} = (1.0 - \text{THRDED}) / (1.0 - WAKE) \]
\[ \text{BP} = \text{REV} \cdot \text{SQRT} (\text{SHP} / 1.025) / \text{SPDADV}^2 \cdot 2.5 \]
\[ \text{PRPDIA} = 0.70T \]
\[ \text{P_RPDIA} > 28 \Rightarrow \text{PRPDIA} = 28.0 \]
\[ \text{NHEFF} = (1.0 - \text{THRDED}) / (1.0 - WAKE) \]
\[ \text{BP} = \text{REV} \cdot \text{SQRT} (\text{SHP} / 1.025) / \text{SPDADV}^2 \cdot 2.5 \]
\[ \text{N} > 1 \\& \\& \text{6} > \text{BP} > 155 \]
\[ \text{BASICD} = \text{FUNC} (\text{BAR}, \text{BP}) \]
\[ \text{PRPEFF} = \text{FUNC} (\text{BAR}, \text{BP}) \]
\[ \text{PITCHR} = \text{FUNC} (\text{BAR}, \text{BP}) \]
\[ \text{PRPDIA} = \text{BASICD} \cdot \text{SPDADV} / \text{REV} \]
\[ \text{PRPDIA} > 0.70T \]
\[ \text{PRPDIA} = 0.70T \]
\[ \text{PRPDIA} > 28.0 \Rightarrow \text{PRPDIA} = 28.0 \]
\[ \text{DELTA} = \text{REV} \cdot \text{PRPDIA} / \text{SPDADV} \]

**Empirical Relation to Calculate Field Effcy.**
\[ \text{PP} = 1.5 \cdot (1.0 - \text{DELTA} / \text{BASICD}) + 0.065 \]
\[ \text{PPP} = 1.0 - \text{DELTA} / \text{BASICD} \]
\[ \text{P} = \text{BASICD} / (\text{BASICD} + 10.0) \]
\[ \text{PFNEW} = \text{PRPEFF} - \text{PP} \cdot \text{PPP} \cdot \text{P} \]
\[ \text{QPC} = \text{PFNEW} \cdot \text{HULEFF} \cdot \text{RRE} \]
\[
\text{SHPNEW} = \frac{\text{EHPN}/\text{NOPROP} \cdot \text{CF} \cdot \text{WEAIRA}}{\text{PFNEW} \cdot \text{HULEFF} \cdot \text{RRE}}
\]

\[
\text{IREVLD} = 2 \\
\text{PRPEFF - PFNEW}>\frac{\text{PRPEFF}}{\text{PRPEFF}}
\]

\[
\text{IREVLD} = 2
\]

\[
\text{SHP = SHPNEW \cdot NOPROP}
\]

\[
\text{REVS = REVS \cdot 1.15} \\
\text{PFNEW = PFNEW}
\]

\[
\text{DBAR < BAR}
\]

\[
\text{BAR = DBAR} \\
\text{SHP GO TO FAIL}
\]

\[
\text{BP OUT OF RANGE}
\]

\[
\text{RETURN}
\]

\[
\text{END}
\]
APPENDIX 2.

FLOW CHART OF THE COMPUTER ALGORITHM
FOR DETERMINATION OF THE CONTAINER CAPACITY

READ IN

LENGTH B.P., BEAM, DEPTH, DRAFT, BLOCK COEFF., SHAFT HORSEPOWER
TOTAL CONTAINER CAPACITY, CONTAINER TIERS, CONTAINER ROWS,
PROPELLER REV'S., STEEL COEFF., SPEED, ENDURANCE, SHAPE COEFF.

DBHM = DOUBLE BOTTOM HT.
CAMBER =
CLEARANCE HATCH COVER AND CONTAINER =
HATCH COAMING HEIGHT =

CALL SUBROUTINE TO CALCULATE THE LIGHTWEIGHT OF SHIP
AND THE CENTRE OF GRAVITY OF LIGHTSHIP WEIGHT

CALCULATE PORT TIME AND SEATIME AND WEIGHT OF
ITEMS OTHER THAN CARGO

ESTIMATE VOLUME OF DOUBLE BOTTOM, ITERATE TO FIND
FUEL IN DOUBLE BOTTOM AND SETTLER TANK, REMAINING
DOUBLE BOTTOM SPACE AVAILABLE FOR BALLAST

CALCULATE CARGO DEADWEIGHT = DISPLACEMENT -
LIGHTSHIP WEIGHT + WT. OF CREW & EFFECT + WT. OF FRESH WATER
+ WEIGHT OF STORE + WT. OF FUEL + WT. OF DIESEL + WT. OF
LUBOIL

CALL SUBROUTINE TO CALCULATE CONTAINER
CAPACITY BASED ON INITIAL GM.

CALL SUBROUTINE TO CALCULATE STATICAL STABILITY

N
LAST DATA

Y
STOP
END

A

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Notes:
ROWSN = BAYS
CNA = ROWS
CNV = TIERS
CNVB = TIERB
CNT = Total containers, Teu
SHAPEC = Shape coefficient

ROWSN = ROWSN + 1.0
CNPR = CNA * CNV
ROWSN = 1.0
CNRI = ROWSN * CNPR
CNRA = CNRI * SHAPEC
NCRA = CNRA
NCT = CNT

NCRA = CNT
CNLOST = CNRI - CNT
NLOST1 = CNLOST / 3.33
NLOST2 = CNLOST / 3.8
NLOST3 = CNLOST / 5.0
N123 = NLOST1 + NLOST2 + NLOST3

NCV = CNV
NREM = NCV - 3
NREM = NCLOST - N123
NPLAY = NREM / NREM
NREMA = NPLAY * NREM

NREM = NREMA

NLOST4 = NPLAY + NREM - NREMA
CLOST1 = NLOST1
CLOST2 = NLOST2
CLOST3 = NLOST3
CLOST4 = NLOST4
PLAYER = NPLAY
CPLYR = CNA * ROWSN
CONT1 = CPLYR - CLOST1
CONT2 = CPLYR - CLOST2
CONT3 = CPLYR - CLOST3
CONT4 = CPLYR - CLOST4

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FKGD = FKG/D
GM = FKM - FKG

GM > GMR

ABS(GMR - GM) < 0.02

G

Y

CNT = CTHLDC + CTDCKC
ICNT = CNT
ICTHLD = CTHLDC
ICTDCK = CTDCKC

RETURN

F

N

RETURN

END
APPENDIX 3. MAIN PROGRAM FLOW CHART BY PARAMETRIC VARIATION OF PRINCIPAL DIMENSIONS

READ IN MAIN DATA

NCB=IFIX((FCB-SCB/0.01)+1)
DO5 JCB = 1, NCB
DO10 JROWS=1,NROWS
CALCULATE BMIN & BMAX

DO20 JTIER=1, NTIER
CALCULATE DMIN & DMAX

FLMIN1=L/DMIN*DMAX
FLMIN2=L/DMIN*BMAX
FLMIN3=V2/7.3818
SLBP=AMAX1(FLMIN1,FLMIN2,FLMIN3)

FLMAX1=L/DMAX*DMIN
FLMAX2=L/BMAX*BMIN
FLMAX3=V2/0.52493
FLBP=AMIN1(FLMAX1,FLMAX2,FLMAX3)

NLB = IFIX((FLBP-SLBP)/1.0) + 1
ND = IFIX((DMIN-DMIN)/0.4) + 1
DO104 KNB = 1, ND

NB=IFIX((BMAX-BMIN)/0.5) + 1

A

DO 102 KNB = 1, NB
DO 30 KLBP = 1, NLBP

TMIN = B/B/TMAX

CALLFREBRD
TMAX1 = D - FREEBOARD

TMAX2 = B/B/TMIN

TMAX = MINIMUM OF (TMAX1, TMAX2)

NDRAFT = IFIX((TMAX - TMIN)/0.5) + 1
DO 40 JT = 1, NDRAFT
FIRST APPROX. TO CONTAINER CAPACITY

CALL EFECHP

B

CALL POWER

(C) > 5.0
(C) < 0.0

BP<6 OR BP>155

CHECK PROP.EFF WITHIN BP-6 CHART

DBAR < 0.45

DBAR > 1.05

CALL DESIGN

LBP < LMIN

C