OFFSHORE SUPPLY VESSEL DESIGN STUDIES WITH APPLICATION OF EXPERT SYSTEMS

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DECLARATION

Except where reference is made to the work of others,
this thesis is believed to be original.

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NOMENCLATURE

Those symbols and their meanings that are not found here are given in the text.

AAC	average annual cost
A_M	midship area
A_W	waterplane area
B	ship beam moulded
B_{jk}	damping matrix containing damping force and moment of inertia per unit velocity
BAR	propeller blade area ratio
BM	height of metacentre above the centre of buoyancy
CAF	compound amount factor
C_B	block coefficient
CF	certainty factor
C_{jk}	restoring matrix containing restoring force and moment per unit acceleration
C_L	coefficient of lift
C_M	midship coefficient
C_P	prismatic coefficient
CRF	capital recovery factor
C_r	camber
C_W	waterplane area coefficient
D	ship depth moulded
D_{er}	height of engine room
D_{tt}	height of double bottom
Dms	deadmass
E	hull numeral
F_j	complex wave force and moment vector per unit wave amplitude
F_n	Froude Number
ft	feet
g	gravitational acceleration (9.81 m/s^2)
GM	transverse metacentric height
gt	gross tonnage
GZ	righting arm

hr	hour
hfo	heavy fuel oil
$H_{1/3}$, $\zeta_{1/3}$	significant wave height
i	interest rate
IMO	International Maritime Organisation
IRR	internal rate of return
ITF	International Transport Workers Federation
ITTC	International Towing Tank Conference
j	mode of excitation and takes the value similar to k for the corresponding modes
J	advance coefficient
k	mode of motion takes 1, 2, 3, 4, 5 and 6 for the surge, sway, heave, roll, pitch, and yaw, respectively
k_o	wave number
KB	height of centre of buoyancy above keel
kg	kilograms
KG	height of centre of gravity above keel
km	kilometres
KM	height of metacentre above keel
Kn	knots
K_Q	torque coefficient
K_T	thrust coefficient
KW	kilowatts
L	length of ship
LBP	length between perpendiculars
LCB	longitudinal centre of buoyancy
L_{er}	length of engine room
L_{OA}	overall length of ship
L_p	length between peak tank
m	metre or mass of ship (Chapter 6)
mdo	marine diesel oil
M_{jk}	mass matrix containing the mass, mass moment of inertia and products of inertia of the body
N	revolutions per minute
nm	nautical miles
NPV	net present value
nt	net tonnage

p	pitch diameter ratio
P	principal
P_B	brake power
P_D	delivered power
P_E	effective power
P_S	shaft power
PWF	present worth factor
QPC	quasi propulsive coefficient
RFR	required freight rate
R_n	Reynolds Number
s	motion displacement
$\dot{s}$	motion velocity
$\ddot{s}$	motion acceleration
s_k	complex motion displacement vector per unit amplitude
$S(\omega)$	wave spectral density
SCAF	series compound amount factor
sfc	specific fuel consumption
SFF	sinking fund factor
S_a	sheer aft
S_f	sheer forward
SHP	shaft horsepower
SPWF	series present worth factor
t	thrust deduction factor
T	ship design draft moulded
V	speed
V_a	speed of advance
w_T	Taylors wake fraction
W_M	machinery mass
W_O	outfitting mass
W_S	steel mass
ρ	density of water
Δ	displacement of ship
∇	volume of displacement
ω	wave frequency
η_{opt}	optimum efficiency of propeller
η_O	propeller open water efficiency
η_H	hull efficiency
η_R	relative rotative efficiency
$\Gamma(x)$	gamma fuction in the spectrum

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SUMMARY

This thesis deals in depth with the design, operational and economic characteristics of offshore supply vessels, including pure supply and anchor handling/tug/supply types. The design characteristics investigated in this thesis include the main dimensions, hullform, stability, group weights, capacity and powering. The hullform of the offshore supply vessel is developed using the initial sketch technique where the vessel is divided into four boundary curves, that is, stern profile, parallel middle body and stem profile. The operational characteristics examine the seakeeping and manoeuvring behaviour, and the modelling of the supply operation of offshore supply vessels. The seakeeping characteristics are analysed using strip theory, while the manoeuvring characteristics are based on established empirical formulae. The modelling of the supply operation simulates the operating pattern of such vessels supplying materials to drilling platforms. Economic studies incorporated in this thesis served as a base for economic evaluation of each design. The required freight rate is used as a measure of merit for the owner operating the vessel, while the minimum charter rate is used if the owner is to charter the vessel.

The computer is used as the principal tool in this thesis and a digital computer program algorithm has been developed to carry out the task. The computer program is written using expert system programming. Instead of using one of the languages used in expert system programming such as Lisp or Prolog, a well known commercial expert system shell, *Leonardo*, is used. The programs have been carefully written so that the user can interact with the system, the interaction can be merely to request continuation of the calculation or discuss the next step, with the system giving guidance, advice and stimulation. In general, three major programs have been developed. They are :-

a. an iterative design program for offshore supply vessels,

b. an interactive optimisation design program which involves mathematical optimisation procedures, and

c. an operational modelling program for the offshore supply vessels.

This thesis also considers methods of incorporating uncertainties in the preliminary design of offshore supply vessels. Apart from reviewing the existing methods of incorporating uncertainties in ship design studies, two methods are examined, Certainty Theory and Bayes' Rule. A program is written to incorporate uncertainties in the selection of main engine and propulsion units for the offshore supply vessels.

CHAPTER 1

REVIEW OF THE DEVELOPMENT OF OFFSHORE SUPPLY VESSELS

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1.0 INTRODUCTION

Support and supply for offshore platforms are key elements in the overall effort for recovery of oil and gas reserves in the outer continental shelf and deeper waters. Supply of construction and operating materials, repair and maintenance capabilities are support functions which must be constantly available on a timely basis to ensure continuous operation. Nevertheless, one of the most demanding functions is the frequent communication with the platform to supply the necessary materials. Obviously, the fastest way of transporting supplies is by helicopters. But helicopters which are used for transporting personnel as their main function, are limited by their carrying capabilities and are very much more costly. Thus transporting supplies by air is used only for small, light and urgent items.

Offshore structures and mobile drilling units may consume very large quantities of materials during their operation. In this context, offshore structures may include any kind of offshore platform whether it is floating or fixed, while mobile drilling units may include any kind of rig for drilling whether it is for appraisal, or development drilling. The total quantity of materials required for each structure varies widely depending upon the type and size of the structures, geological and environmental condition, and the activities that are carried out. On the other hand, space and capacity of the offshore structures to accommodate supplies are limited. In the case of mobile drilling units, this limitation is significant. Therefore sufficient supplies must be transported frequently, and the only way is by using offshore supply vessels.

During the past three decades, because of the rapid worldwide development of offshore oil fields, we have seen not only bigger, faster, and more seaworthy supply vessels built, but have also witnessed the use of these vessels adapted for many different roles including seismographic vessels, oceanographic research ships, tenders for deep-diving submarines, telephone cable-laying vessels, anchor handling vessels, fire-fighting, ice-breaking, oil spill recovery vessels and seagoing tugs. Figures 1.1 to 1.4 show the statistical data of growth for the offshore supply vessels since 1980 to 1991 [8].

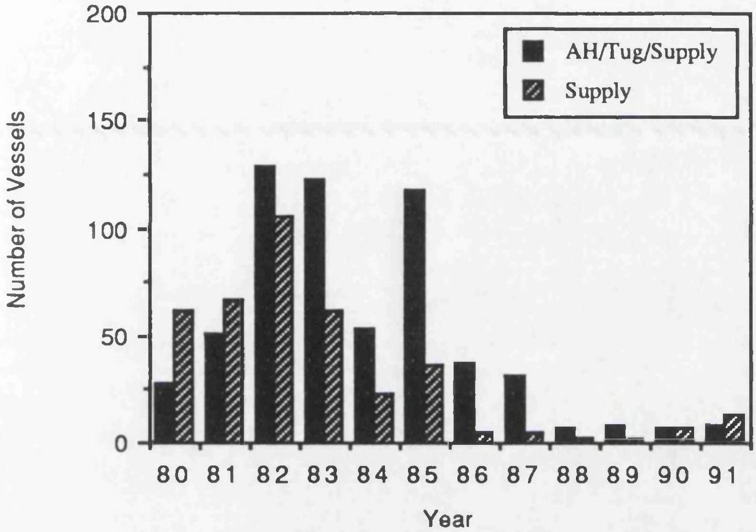

Fig. 1.1 Number of Vessels Built From 1980 to 1991 Worldwide

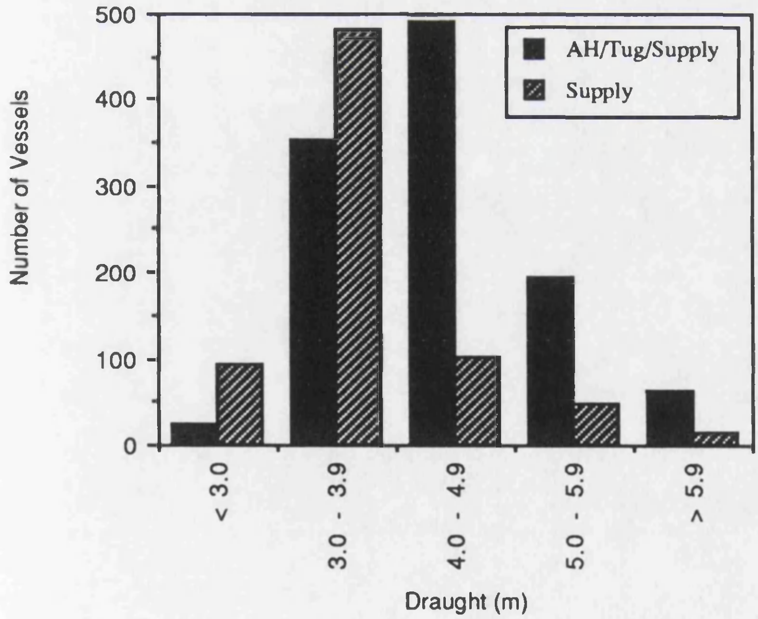

Fig. 1.2 Draught Analysis of Offshore Supply Vessels

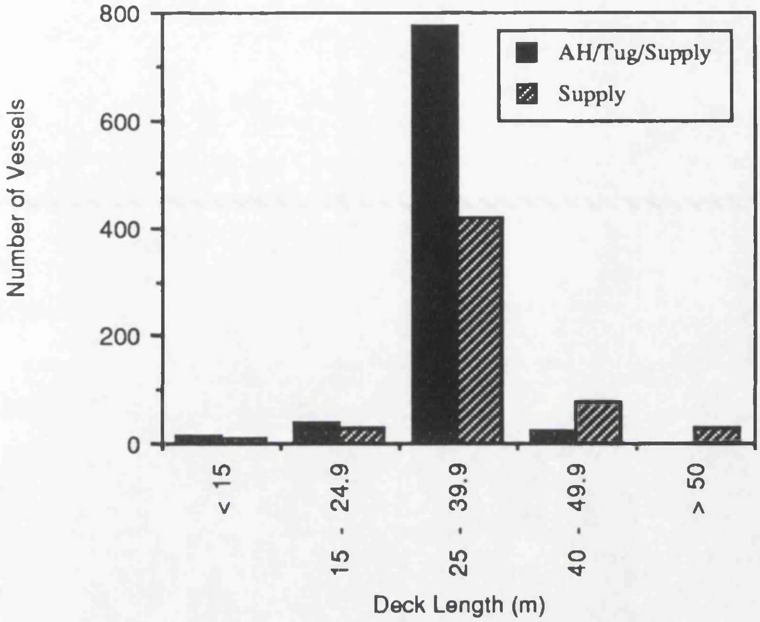

Fig. 1.3 Deck Length Analysis of Offshore Supply Vessels

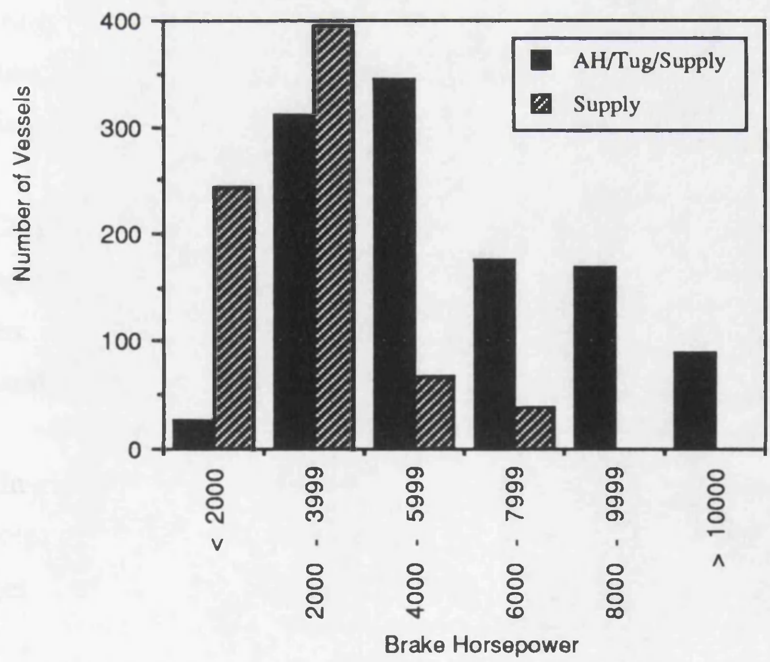

Fig. 1.4 Brake Horsepower Analysis of Offshore Supply Vessels

In early 1990, a resurgence of interest in the offshore supply vessel market for world wide especially UK North Sea operations was realised due to the levels of exploration activity, which were close to an all time high. Utilisation of all supply vessels at mid February 1990 in UK sector of the North Sea was 93% for anchor handlers, and 90 - 95% for platform support vessels which was the highest level for some considerable time [38]. Since the offshore industry's peak in 1982 - 83 and the market's low point of 1987, various self correcting features and aggressive reorganisations have helped the world wide supply vessel industry weather the storm.

Offshore supply vessels are operated on either a spot or long term charter basis. The spot market, normally involving durations of up to 30 days, is a volatile one, usually characterised by high day rates and mainly rig moving. As demand for spot market supply vessels increases so inevitably do the day rates. Day rates have started to increase due to the upsurge in exploration activity, pipelaying and construction but the ample supply of vessels retains keen competition.

The long term charter market tends to be dominated by operators who have a number of fields to service and substantial exploration programmes, both of which merit fleet charters ordered in advance. Most of the major oil companies deploy fleets of supply vessels on a long term basis for all their activities, other than rig moves. Demand is high at the moment especially for platform supply vessels. This looks set to continue, assuming the high exploration activity promised does indeed materialise.

Day rates are beginning to reach the levels achieved in 1984/85 prior to the oil price collapse. Vessel owners are now doing what they can to push up prices and recoup losses incurred over the last few years. Pressures to get rates up on the back of demand seems justifiable.

In early 1991 [38] optimism prevailed about prospects for vessels. The season was anticipated to be better than 1990, with several offshore construction projects expected to get under way as well as a number of through-season contracts already awarded giving beneficial results to offshore supply vessel activities. However viewed in retrospect from 1993, this optimism was misplaced.

1.1 TRENDS IN OFFSHORE SUPPLY VESSEL DESIGN

Offshore oil operations commenced in the Gulf of Mexico during the late 1930's and, interrupted by World War II, accelerated following the war. Heavy materials and equipment such as drilling pipe, casing and tubing were transported to the drilling location via tugs and barges. Drilling mud and cement were taken to the platforms in bags during early stages of offshore drilling and several type of surplus vessels such as LCM's and minesweepers were used initially to carry these and similar materials. While some of these vessels were modified to enable the carriage of drilling pipes and other heavier materials, they never proved entirely suitable and the tugs and barges continued to transport those heavy and bulky materials.

By the mid 50's, wells were being drilled 30 to 50 km offshore and the effects of rough seas on the tug/barge combinations, and the resulting delays, established the need for a vessel with better manoeuvrability and seakeeping qualities. As a result, a new design was introduced. This first generation of vessel established the trend for future development of the design of offshore supply vessels.

These early vessels were approximately 30 to 40 m long with a 10 m beam and a 2.5 to 3 m depth. The majority of these vessels had a short forecastle containing chain lockers, galley, dining area and quarters, with an additional deck above, topped by the wheelhouse. The main deck aft of the forecastle, which constituted approximately two thirds of the length of the hull, was devoted to deck cargo space. Drilling water, potable water and fuel oil were carried in the integral tanks of these vessels for delivery to the offshore platforms. The drilling water was simply fresh water carried in the ballast tank. Drill pipes, casings, tubings, drilling mud (dry) and cement were carried as deck load. The big advantage of the supply vessels over the tug/barge combination, in delivering heavy materials to platforms, were that they possessed better manoeuvrability and the capability of operating in harsher environments as well as having a faster speed.

In the early 1960s, the jack-up drilling rig and its attendant supply vessels began to migrate to other parts of the world, notably the Arabian Gulf and the southern North sea where the oil companies began to drill for gas, soon making discoveries off the coast of Holland. The increasing number of jack-ups in the North Sea were still supplied mainly by American vessels from the Gulf of Mexico, but both British and European shipping companies, alive to the new opportunities, began to build their own supply vessels, much in the style of their American counterparts and still powered by two engines, each of about 375 kW with twin rudders. The only serious concession to this new work being carried out was the provision of a large window at the after end of the bridge to allow the captain to see out.

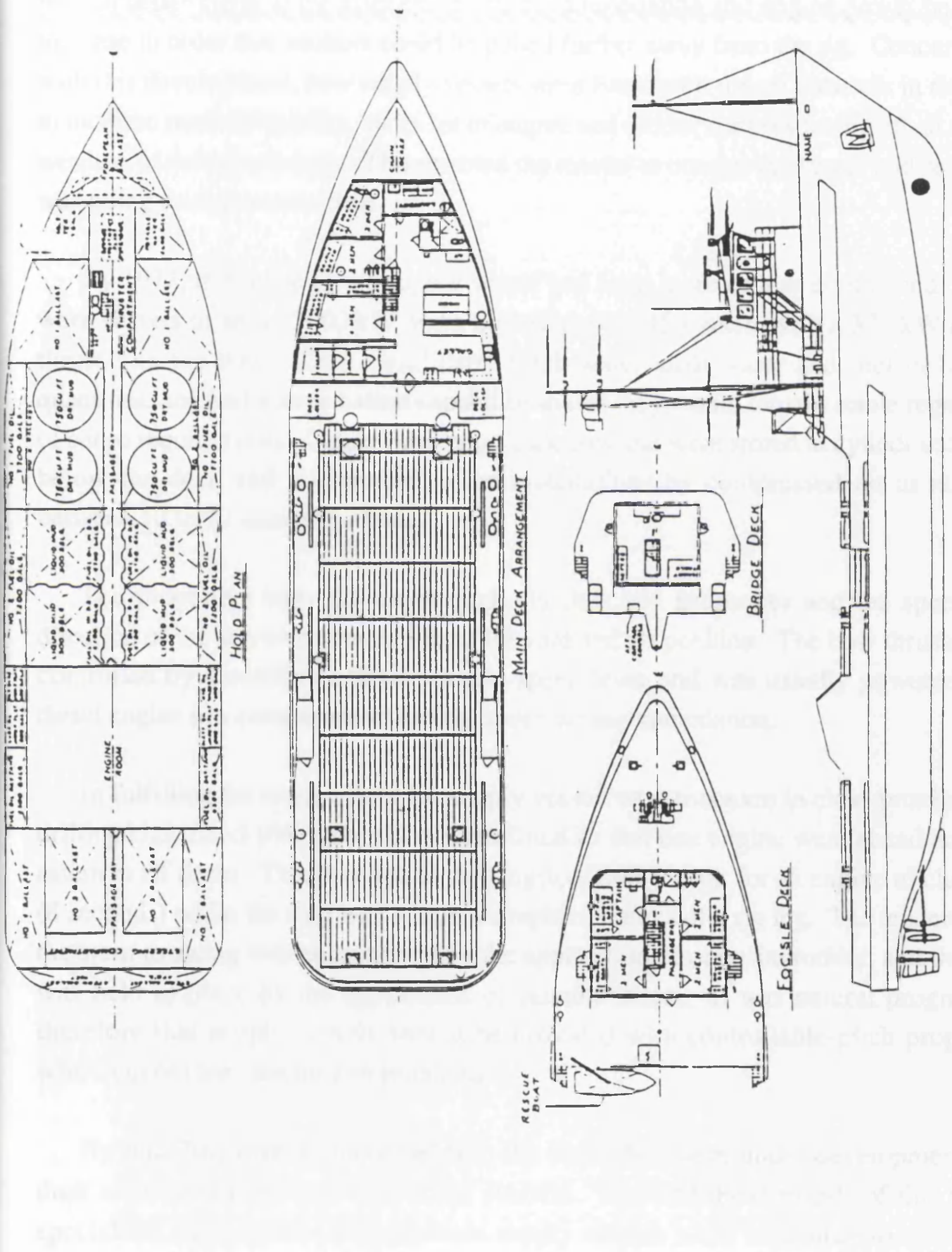

Fig. 1.5 Typical Gulf of Mexico Offshore Supply Vessel [11]

With the requirement to lay anchors, supply vessels in the Gulf of Mexico had rollers added to the stern and a diesel power winch bolted to the after deck while in Europe, some supply vessels were fitted with large A-frames at the stern, so that the anchors could be lifted clear of the water and then dragged abroad. However, the A-frame was soon dispensed with and rollers became normal. Winches were soon being housed under cover at the after end of the accommodation and engine power began to increase in order that anchors could be pulled further away from the rig. Concurrently with this development, new supply vessels were fitted with tunnel thrusters in the bow to increase manoeuvrability, and a set of engine and rudder controls facing aft, at the aft window of the wheelhouse. This enabled the master to control the vessel and see what was going on at the same time.

By 1972, the shape of the supply vessel had been more or less established. They were vessels of about 3000 kW and a bollard pull of 45 tonnes, with a 375 kW tunnel thruster in the bow. They could carry fresh water, drill water and fuel in limited quantities, and had a large ballast capability so that they would remain stable regardless of cargo requirements. Cement and other bulk powders were stored in cylindrical tanks below the deck and transported to the installations by compressed air at rates of between 10 to 20 tonnes per hour.

The propellers were driven through clutches and gearboxes and the speed and direction of the screws controlled from forward and aft position. The bow thruster was controlled by a combined direction and speed lever and was usually powered by a diesel engine in a compartment directly under the accommodation.

In fulfilling the requirement for supply vessels to manoeuvre in close proximity to drilling rigs, fixed-pitch propellers were fitted so that one engine went ahead and one astern at all times. This was due to the length of time it took for an engine to clutch in (8 seconds) while the ship was within a couple of metres of a rig leg. The tendency for the stern to swing was encountered by the application of opposite rudder, and the bow was held in place by the application of suitable thrust. It was natural progression therefore that supply vessels should be provided with controllable-pitch propellers which cut out the clutching-in problems.

By mid 70s, several major fields in the North Sea were under development, and their associated pipelines were being planned. To fulfil the demands of this phase, specialised pipe carriers and platform supply vessels were beginning to come into service. Notable among the pipe carriers available in the mid 70s was the OilChallenger, built with the accommodation aft.

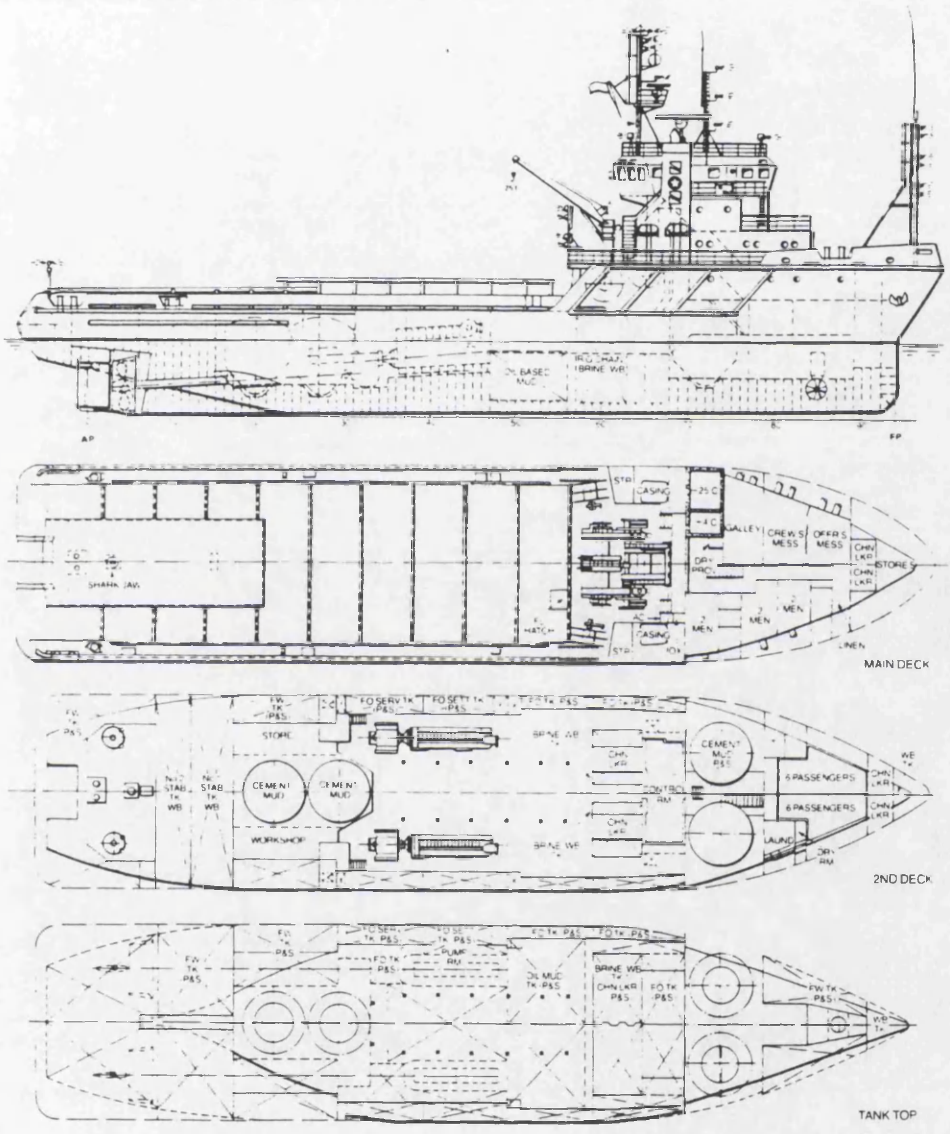

Fig. 1.6 Typical North Sea Offshore Anchor Handling/Tug/Supply Vessel [34]

Throughout the period, the marine industry was supplying more and more sophisticated anchor handlers and by 1976, there were several boasting an available power of more than 6000 kW. The increase in power of the North Sea supply vessels was also to lead to an increase in power of vessels built elsewhere, though of a lesser order. In Europe, the supply vessel was moving further and further away from the original Gulf of mexico concept., the first thing to change being the shallow draught. To convert the extra power into bollard pull, large screws were fitted which together with the demand for greater deadmass increased draft.

Systems for the carriage of bulk cargoes were also developed. The early horizontal cement tanks were being superseded by vertical hoppers with higher pressure pumping system capable of discharging up to 30 tonnes per hour. Development in this area has continued, and in the 80s pumping rates of up to 80 tonnes per hour became commonplace. Dedicated tanks for unusual fluids used in the drilling operation also began to appear, and ballast tanks capable of doubling as rig chain lockers were fitted to the anchor handlers. The cargo deck of most of these vessels is covered with thick wood sheathing held in place by boundary angles. As with any cargo vessels, the wood serves to protect the deck plating during cargo transfer operation. The shell plating is protected as much as possible by the installation of rubrails or guards usually made of thick wall pipe sections welded to the shell at the gunwale and at other high-wear locations. Fenders of heavy truck tyres attached to the hull with chains are also used to minimise damage to the hull if contact takes place.

The latest development in the design of the offshore supply vessels coincided with the increased offshore activities in the Arctic region. From their initial mission strictly as supply tenders for shallow water operations, they have expanded to undertake towing and standby service, fire-fighting service, anchor handling, rescue craft and recently as icebreakers for the Arctic exploration. Their capabilities increased in several directions primarily dictated by the nature of their operation area. Hence, such supply vessels require much greater capacity, speed, endurance and seaworthiness. Hostile areas are also associated with the high environmental loading on floating drilling units from wave and/or ice action which led to the heavy duty mooring requirements. As a result, there is a demand for greatly increased anchor handling ability by the attendant offshore supply vessels. For Arctic work, offshore supply vessels posses features such as icebreaking capability, spoon bow, ice lubricating system, specially painted and double skinned hull.

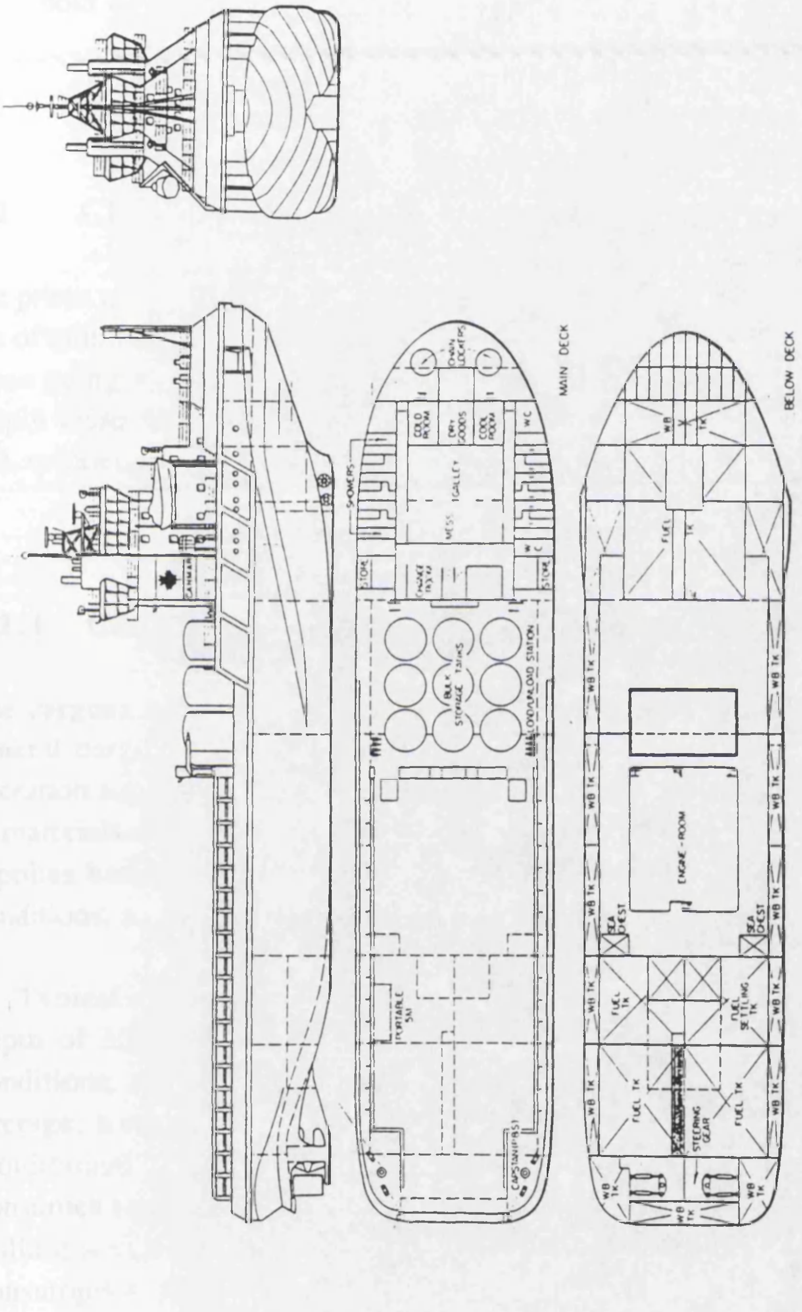

Fig. 1.7 Typical Arctic Offshore Supply Vessel [32]

In general, a modern offshore supply vessel is equipped with twin screws having power more than 8000 kW, is highly manoeuvrable, having controllable pitch propellers, kort nozzles, multiple thrusters, and a bollard pull in excess of 150 tonnes. It can handle up to 30 tonne anchors, and may have fire-fighting capabilities with up to 50 m^3/hour of seawater and smothering foam.

1.2 CRITERIA OF OFFSHORE SUPPLY VESSELS

The prime objectives of a supply vessel vary according to an owner's requirement from one of minimum size for short range operation in a relatively calm environment to a full ocean going supply of large capacity and power. Basically, the criteria of the offshore supply vessel can be discussed broadly in terms of its cargo carrying capability, bollard pull, manoeuvrability and seakeeping qualities.

1.2.1 Cargo Carrying Capability

The cargoes carried on board the offshore supply vessels are, unlike those of the general cargo vessel, specific to match the particular requirement for the offshore operation such as drilling and production. A drilling rig may consume large quantities of materials during the drilling of an offshore well. In essence, the type and amount of supplies basically depends on the type and size of rig, geological and environmental conditions, and the phase of offshore activity.

Typical daily consumption rates for the drilling of an exploration well down to a depth of 3500 m in 60 days is given in Table 1.1. Depending on the working conditions, an exploration well could take from 40 to 200 days to be completed. On average, a rig is expected to drill 3 to 4 wells in a year dictating a supply material requirement of 20000 to 40000 tons. Development drilling on the other hand, consumes similar types of material but at faster rates due to the nature of development drilling which is more predictable and therefore allows rapid progress. The average consumption for development drilling is generally in the range of 10000 to 16000 tons each well per year [33].

The materials required to complete an uninterrupted drilling operation at a minimum cost can be divided into two categories, that is, bulk material and deck cargo.

Table 1.1 Average Daily Consumption of Material During Exploration Drilling [33]

SUPPLIES	MAIN PURPOSE	DAILY AVE. CONS. (tonnes)	
Cement	Preventing leakage during drilling Protect against corrosion	Mean Maximum	10 15
Casing	Preventing wall from falling in Obtaining controlled production	Mean Maximum	10 15
Mud	Raising drill cuttings to surface Well analysis	Mean Maximum	15 25
Water	Potable and drilling water	Mean Maximum	30 60
Fuel	Machinery and rig movements	Mean Maximum	20 50
Misc. Equipment		Mean	10
	TOTAL	Mean Maximum	95 165

1.2.1.1 Bulk Material

a. Types of Bulk Material

A major portion of the cargo for offshore installation is carried in cargo tanks and discharged by hose. These cargoes may be liquid or dry powder. Liquids include gas oil, potable water, drill water or brine, and oil based mud. Dry powder solids include cement, barytes and bentonite and discharge is by pneumatic hose. The cement is mixed for grout and the barytes and bentonite are used to make drilling mud. Oil based mud is more convenient to make ashore.

Intergral tanks are used for liquids and hopper tanks for the solids. Drill water tanks may also be used for ballast. Modern vessels may carry a considerable amount of potable water and the rate at which it can come aboard from shore mains may dictate loading trim.

b. Carriage of Oil-Based Mud

The most difficult bulk cargo to carry is oil based drilling mud, which is a mixture of detoxified diesel oil in which barytes are suspended, and other chemicals particular to the mud companies.

Offshore supply vessels oil-based mud tanks are either purpose built, in which case they are usually rectangular with no excessive projections or framing, or converted from fuel or water tanks. In the latter case, they will probably contain obstructions of one sort or another which make them difficult to clean.

Since the liquid is a suspension rather than a solution, some effort must be made to maintain the solids in suspension during carriage. This is done by fitting agitators or circulating pumps. Agitators are some form of propeller or vane system, which rotates under hydraulic power while the mud is in the tank. These propellers are fairly effective but are more expensive than the conventional circulating system.

Circulating systems consist of pumps which take the liquid from the main suctions and pump it back to the tank through pipes, hence keeping the liquid moving. The pipes from which the liquid is discharged back into the tank are usually fitted with nozzles and either extend along the top of the tank, or the bottom, and in some cases both. The mud is sprayed from the nozzles to increase agitation.

c. Discharge of Bulk Cargoes

All bulk cargoes are discharged through hoses. If the vessel is tied up to the rig, any number of hoses may be connected. If the vessel is dynamically positioned under joystick control there may be a safe limit to the number of hoses connected in case rapid disconnection is needed. The cargo that takes longest to discharge must get priority of hose connection.

Dry bulk cargoes are probably the most difficult to deal with and, on older supply vessels which cannot produce high pressure air, their discharge is a long and tedious operation. The most common manner in which dry bulk is carried is in hopper tanks with the discharge line running from the bottom. The tank is pressurised with air, so that when the discharge valves are opened, the cement or other cargo is pushed along the line to the rig.

Some modern vessels operate in two stages, and use conventional rectangular tanks for carriage and hoppers for discharge. These may consist of four rectangular tanks and two hoppers. Cement is pumped into one of the hoppers. When it is full, it is pressurised and discharged to the rig. While this is happening, cement is pumped into the second hopper. In this way continuous discharge can take place and, since the hoppers are smaller, discharge should be more rapid.

1.2.1.2 Deck Cargo

a. Tubulars

This includes drill pipe, riser joints or test tubing which may be required during drilling of a well to replace or supplement that already carried aboard the rig. However, much more important during an exploration well is casing which will be required at different stages of a well in sizes ranging from 762 or 915 mm (30 or 36 in) conductor down to 178 mm (7 in) casing or liner. The size and mass of casing diminishes as the well is drilled deeper, but a greater length of casing is required. Failure to have the right casing out at the rig at the right time can be costly in terms of lost rig time and in some circumstances can be potentially hazardous where, for example, it is required to case off an unexpected high pressure zone. Accurate planning of supply operations to ensure that casing is taken out to the rig at the right time and in optimum loads is essential. The mass and number of joints in each string of casing can easily and accurately be calculated. Whether or not a single supply vessel can carry a full string will depend on three factors:

a. total maximum deck loading of the vessel,

b. whether the deck is long enough for three or two lengths of casing, and

c. whether, when stowed, the centre of gravity of the cargo would be within approved stability limits for the vessel.

Generally speaking, pure supply vessels operating in the North Sea can accommodate three lengths of casing on deck, while many anchor handling/tug/supply vessels can only accommodate two lengths since the anchor handling winch intrudes into what might otherwise be open deck cargo.

b. Containerised Cargo

In areas such as the North Sea where weather conditions may be hostile, other deck cargo is frequently containerised. This serves both to protect the cargo and also to assist discharge at the rig.

While standard-size ISO containers may be used and while many contractors on the rig, such as logging contractors, mobilise their equipment in standard container-size modules, the use of mini-containers is more usual during drilling operations. These are now normally used for the regular movement of food, catering and general stores to the rig and also conveyance of palletised bags of drilling chemicals and drilling bits.

Other specialised containers handled as cargo deck for offshore supply vessels include small, sealed aviation fuel tanks for helicopter refuelling, garbage compactors and security containers for the carriage of explosives and low level radioactive sources required in conjunction with the exploration programme.

c. Other Deck Cargo

Other items of deck cargo which cannot easily be containerised must also be carried when required. This will include spare parts or replacement equipment which is often required as quickly as possible to minimise rig downtime. Examples of such equipment may be anchors, anchor-chain, heavy blocks or even complete pumps or generator sets. In each case, the safe carriage to the rig will depend upon proper stowage and securing on deck; incidents of deck cargo lost overboard in the voyage may be rarer than ten years ago but are still not unknown. Efficient pre-slinging of the cargo before the supply vessel leaves its base port is also likely to contribute to the prompt and safe discharge of the cargo at the rig.

Apart from these bulk materials and deck cargo, personnel and certain high value light mass equipment have to be transported to the rig. In areas such as the North Sea, helicopters have come to dominate this role and personnel are rarely moved to and from an exploration rig by supply vessel. Nevertheless, most supply vessels and anchor handling/tug/supply vessels still have rather spartan accommodation for up to 12 passengers in two or three cabins, which could be used if required.

The carriage of deck cargo involves a number of considerations, which in turn will affect the quantity of cargo that may be carried. The most important factor is the liability to damage in heavy seas. The need for convenient discharge at the rig necessitates an open deck, which has the disadvantage of making stowage arrangements extremely vulnerable to a severe sea state. The carriage of drill pipes and casing requires the use of special retaining rails and chain arrangements for lashing down the pipes. These chain arrangements need to incorporate quick release equipment to facilitate discharge at the rig.

All types and mixtures of cargo need to be considered at the design stage. Each voyage may impose particular limits on the cargo able to be carried by virtue of deadmass, hull cargo capacity, open deck space or stability. It will be an unusual cargo that reaches all the limits and normally any one limit will predominate. The trend of cargoes demanded by the oil industry in future development is important. Unless it is foreseen the vessel may have a short life before it is replaced by a more suitable design.

1.2.3 Bollard Pull and Winch Rating

A criterion which is central to the design of offshore supply vessels with towing and/or anchor handling facilities is the bollard pull. Bollard pull, the measure of the ability of the vessel to provide towing force, is usually at its maximum at zero ship speed reaching perhaps 100 to 150 tonnes force for the more powerful vessels.

The earliest British offshore supply vessels had as little as 1500 kW available, with a bollard pull of 30 tonnes and winches capable of lifting no more than 50 tonnes. By 1972, the vessels had become a little larger, the then most powerful vessel was equipped with 3375 kW giving a bollard pull of 45 tonnes. Most of the recent vessels are equipped with four engines producing 10800 kW giving a continuous 150 tonnes of bollard pull.

The importance of the bollard pull capability of an offshore supply vessel is reflected in the long accepted emphasis on hull form and propeller design employed by designers. Due to the fact that the vessel is designed primarily as a readily available source of high thrust and manoeuvrability, the most efficient length to available power relationships generally accepted in shipping are seldom, if ever, utilised.

Most winches for towing and anchor handling of these vessels are electrically or hydraulically operated and are normally of the type referred to as 'waterfall'. As the name suggest, these comprise basically two wire drums, one mounted slightly higher and behind the other. The winch is positioned about midships, with operation aft over a flat stern deck. Usually the raised drum is equipped with a wire guide arrangement and is intended for towing functions, whilst the lower drum is used for handling rig anchors in conjunction with the rig's own anchor handling winches.

In the earlier design of offshore supply vessels, means of stopping the wires were borrowed from conventional marine anchoring and towing systems. With the passing of time, a number of improvements have been made and as a result a number of hydraulically operated systems are available. They all incorporate a pair of hydraulic posts which lift from the deck and trap the wire between them, some of these having plates on top which turn inwards, preventing the wire from escape. The posts are known as 'towing pins' or 'pop-ups', and the plates on the top as 'elephant feet'. The three commonest forms of securing system are the Ulstein 'Shark's Jaw', the Kamfork and 'Triplex Gear'.

1.2.4 Manoeuvrability and Station Keeping

Offshore supply vessels, unlike conventional cargo carriers, require a high degree of manoeuvrability and station keeping as most of their operations are in the open seas. The limiting environmental conditions in which a dynamically positioned offshore supply vessel can maintain station affect significantly the economics of its operation. The environmental requirements for station keeping of a dynamically positioned vessel influence both the total installed power and the size, number and arrangement of the thrusting units. These in turn affect other parameters such as fuel consumption, fuel capacity, engine room size and crew numbers.

The earlier vessels used rudders for manoeuvrability and station keeping but this combination provides inadequate control for specific low speed manoeuvres which are essential features of the modern offshore supply vessel for its operational activities that include:

a. maintaining station in open unprotected seas or in close proximity to the service offshore structure,

b. coming alongside moorings in open seas,

c. approaching, berthing and leaving harbour quay or dock system,

d. navigation in restricted channels,

e. backing-up to an offshore structure in varying sea states, especially when adverse weather conditions prevail,

f. anchor handling activities including those focused around the laying and breaking out of both mooring anchors and chains, and

g. manoeuvring reasonably while restricted by tow-wires, rig anchors and cables, the vessel's own anchor and cable, or other charter requirement.

These low speed manoeuvres have to be implemented by manoeuvring control devices such as bow and stern thruster units and main propellers which could provide differential thrust. The manoeuvring control devices while performing the above operations also enhance the supply vessel's directional stability, improve the vessel's rate of turn at normal operating speeds and improve its holding capability.

The types of manoeuvring devices which are used are normally selected on the basis of individual preference of each offshore supply vessel operator, although the selection is influenced by successful results of existing vessels. However, the actual choice of the manoeuvring device will be ultimately reflected by the type of operational roles which are demanded from the offshore supply vessel and various other criteria such as degree of reliability, sensitivity to damage, maintenance, level of sophistication and initial cost.

Single-stick manoeuvring capability is now a requirement for virtually all vessels operating in the North Sea, essentially to allow cargo operations to take place without the use of securing ropes, and allow the master to handle the vessel for very long periods. In essence, the joystick is connected to a computer which is interfaced with the gyro-compass to maintain the set heading. When the stick is moved in any direction, the computer activates the engines, thrusters and rudders to move the vessel in that direction. The basic ability of the system to maintain the heading is its most useful component, and beyond this, the ease of use depends on the vessel's hardware, engines, thrusters and rudders, and the sensitivity which is designed into the control and programming of the software.

1.2.5 Other Major Criteria

Apart from the three major criteria explained above, several other secondary factors which are significant to the offshore supply vessels are as follows :

a. *Fuel Capacity* which is a measure of the range the vessel is capable of operating and the longest period it can work without interruption of services.

b. *Cruising/Towing Speed* which is the measure of the vessel's mobility and the ability to deliver its services or tows to their destination.

c. *Ice Classification* which is necessary if the vessel were to be used in the Arctic region.

d. *Fire Fighting Capability* which is an added advantage which operators look for.

e. *Auxiliary Equipment* such as deck cranes to facilitate buoy and anchor handling.

1.3 PROFITABILITY OF OFFSHORE SUPPLY VESSELS

The profitability of an offshore supply vessel is principally judged by its annual utilisation percentage. To keep this at an optimum, the thrust during planning and engineering stages has to be concentrated on keeping its utility to a maximum. Like any other product, it has to be competitively aimed to suit the market and as wide a market as possible. In a rapidly changing market, to acquire equipment which requires large capital investment, and a relatively long engineering and construction cycle, it becomes a matter of good foresight, calculated risks and good judgement. This can be accomplished by the following factors.

a. Keeping well informed about the offshore oil and gas industry. This is necessitated by the ever changing geographical theatres, environment, modes of operation and regulations.

b. Keeping in constant view the technological changes and development in the exploration and development drilling phase operation. This is imperative due to the fact that inadequacy of supply vessels to perform up to the capabilities of the latest generation of exploration and development drilling phase can seriously hinder the latter's operation.

c. Keeping pace with, and anticipating changing national and international regulations and policies.

d. Allowing at the design and planning stages, flexibility in the vessel for future modifications to meet the changing demand of the industry.

e. Constantly assessing and reassessing the quantitative requirements of the market with an overall view towards the equipment under protection. This should be done to prevent oversupply, which results in idle equipment, and hence a lower return on investment.

f. Having a well designed vessel, optimised for its function and ease of construction, with a minimum of capital and maintenance cost and downtime.

g. Standardising major wear and maintenance items in large fleets, (for example machinery, shafts, propellers, rudders, and steering systems) in order to have a readily available spares with a minimum amount of capital tied up in inventory.

1.4 CONCLUSION

In an industry highly dependent on known exploitable resources and changing regulations and legislation affecting their development, the possibility of short or long term oversupply situations should be kept under consideration. Nevertheless, the offshore supply vessels are highly versatile and are capable of a large number of alternative employments, such as :

a. small diameter pipe or cable laying,
b. offshore structure maintenance,
c. oil field and harbour fire fighting and pollution control,
d. supertankers berthing,
e. used as naval auxiliaries,
f. feeder vessel service between shallow harbours and motherships,
g. towing container, oil or general cargo barges,
h. oceanographic or seismic survey vessels,
i. development of ocean thermal energy conversion stations,
j. wellhead service vessels, and
k. fishing trawlers.

Offshore supply vessels have altered in response to changing areas of operation and the need to increase their weather window. Largely, this has been a matter of increased size in the northern North Sea but experience and improvement have reflected the demands of the oil industry.

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CHAPTER 2

MAIN PARAMETERS OF OFFSHORE SUPPLY VESSELS

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2.0 INTRODUCTION

Design data collected from existing vessels have always been of great importance to the naval architect. When kept up to date and suitably analysed, simple relationships can be developed to aid initial sizing of new designs. With this in mind, a review of the principal parameters of twenty pure supply vessels and twenty vessels with various functions such as anchor handling, supply and towing built in the last decade is analysed. This study is done with an aim to show trends in the principal parameters of such vessels. Plots illustrating these parameters are shown in order to provide guidance for designers, owners, and operators in planning future vessels, so as to maximise their capabilities and performance.

In order that the study is valid, certain criteria is adopted in choosing the vessels which include:

a. fitted with twin screws,
b. propulsion by medium speed geared diesel engines,
c. raised forecastle with large open deck aft.

All the vessels with anchor handling, supply and towing facilities are fitted with a deck winch.

2.1 MAIN DIMENSIONS

Some general observations may be made concerning the main dimensions of ships which are usually taken to be length, breadth or beam, depth and draught. Since the surface of a ship represents cost and its volume earning power, the simplest possible analysis would indicate that all ships should 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 dimension while others are secondary.

2.1.1 Length/Beam Relationship

Offshore supply vessels have length/beam ratio between 3.70 and 4.50 as shown in Fig. 2.1. For such vessels, beam is essential for stability and the working deck breadth is maintained over as long a length as possible. The upper deck line aft gives good protection to the propeller and maintains the working deck area. The forecastle deck also requires area which is gained by flare which helps to protect the deckhouse and navigating bridge.

2.1.2 Beam/Depth Relationship

This relationship is primarily one that governs stability since KG is a function of depth and KM is largely a function of beam.

Figure 2.2 shows a plot of depth against beam for offshore supply vessels and indicate that ratios are between 2.10 and 2.70.

2.1.3 Draught/Depth Relationship

Offshore supply vessels are typified by broad beam and shallow draught. Figure 2.3 shows that most of these vessels are built with ratio of depth/draught of between 1.20 and 1.30.

A shallow hull depth helps keep the vertical centre of gravity of deck cargo low. Since the beam/draught ratio is high, freeboard requirements may be governed by the need to keep the deck edge out of the water at relatively low angles of heel rather than the minimum requirements of the load line rules. Consequently, the working freeboard is generally associated with a design draught rather than the lesser freeboard for maximum geometrical draught.

2.1.4 Deck Area/(Length x Beam) Relationship

Characteristically, most offshore supply vessels have superstructure in the forward quarter length, leaving a large proportion of length aft for deck cargo. Figure 2.4 shows that most vessels have a ratio of between 0.4 and 0.5 of deck area over the product of length and beam.

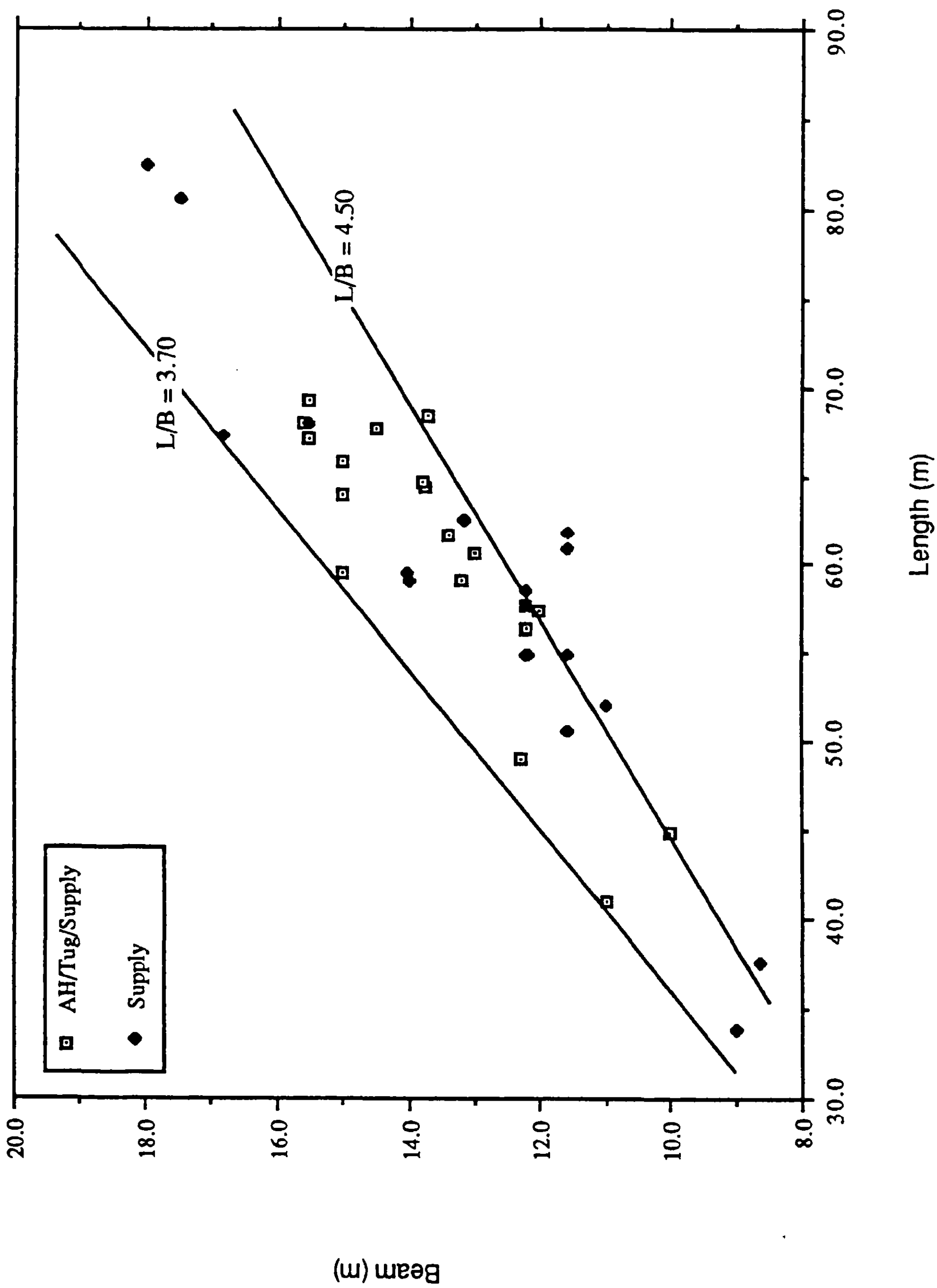


Fig. 2.1 Relation Between Length and Beam

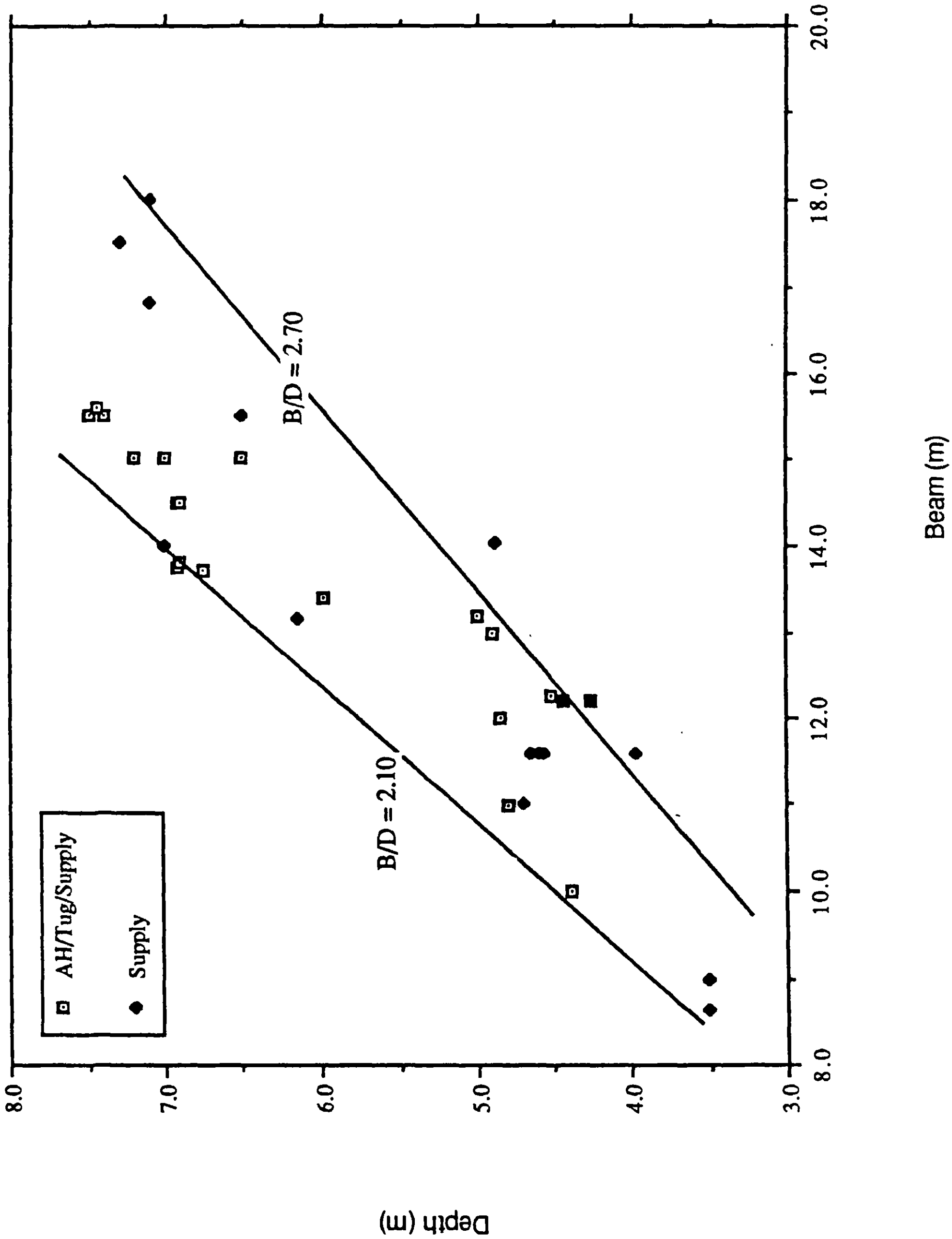


Fig. 2.2 Relation Between Beam and Depth

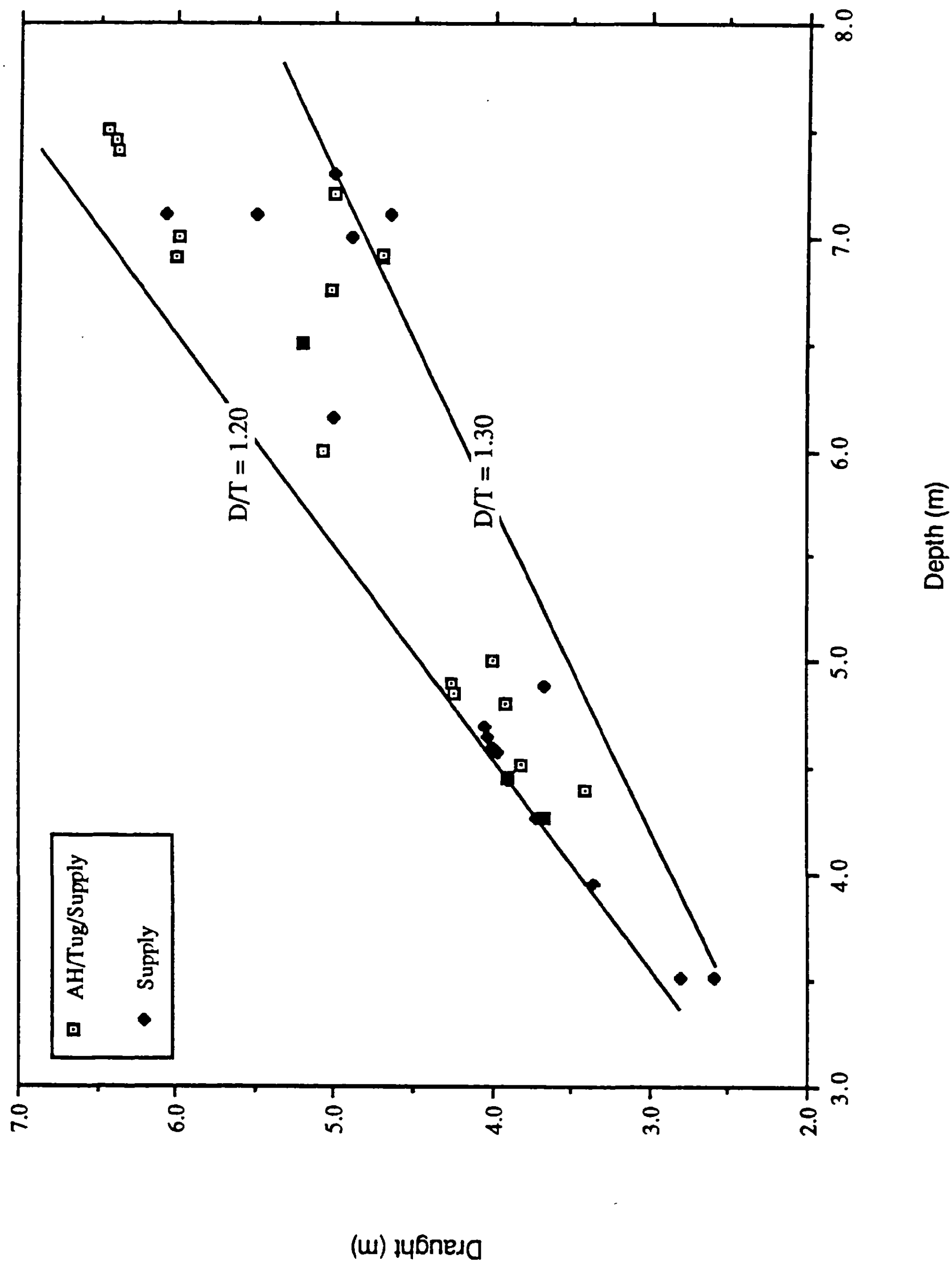


Fig. 2.3 Relation Between Depth and Draught

Table 2.1 Difference Between Operating and Minimum Freeboard

Name of Vessel	LBP (m)	Beam (m)	Depth (m)	Draught (m)	C_B	D - T (m)	Min. Freeboard (m)
Seaforth Sovereign	55.20	13.15	6.15	5.00	0.748	1.15	0.742
Seaforth Emperor	60.00	16.80	7.10	5.49	0.735	1.61	0.978
Stad Ulstein	76.21	18.00	7.10	4.65	0.743	2.45	1.185
Stirling Elf	46.61	11.00	4.70	4.05	0.766	0.65	0.539
Star Capella	61.50	15.50	6.50	5.20	0.718	1.30	0.914
Pacific Bear	35.01	10.99	4.80	3.89	0.677	0.91	0.364
Seaforth Atlantic	62.72	14.50	6.90	4.70	0.590	2.20	0.962
Seaforth Centurion	58.60	15.60	7.45	6.40	0.650	1.05	0.976
Oil Terrier	53.01	13.20	5.00	4.00	0.738	1.00	0.642
Maersk Handler	56.42	13.80	6.90	6.00	0.620	0.90	0.880

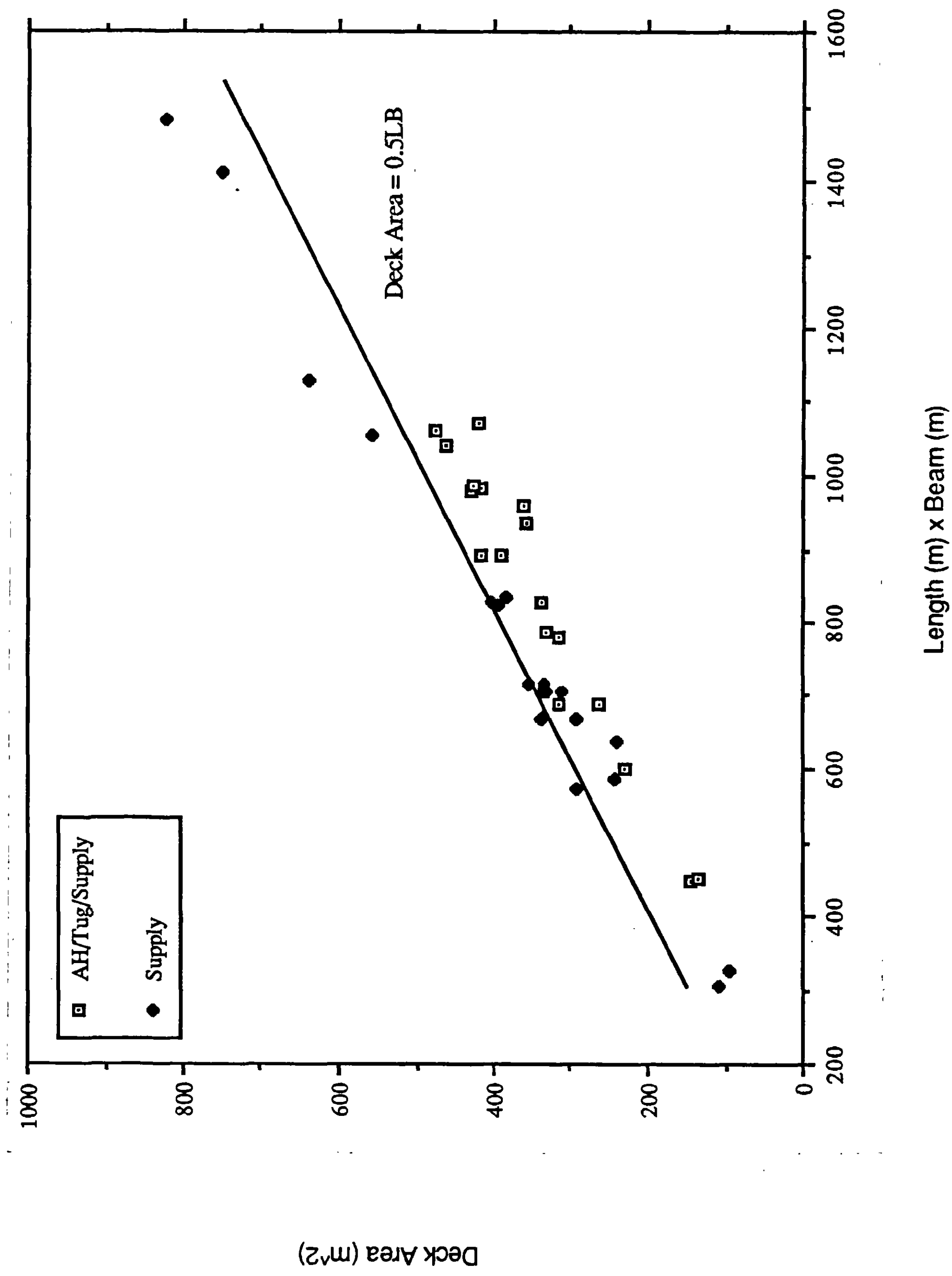


Fig. 2.4 Relation Between (Length x Beam) and Deck Area

2.1.5 Length, Speed and Deadmass Relationship

A common method of evaluating length of a ship in preliminary design is to use a formula of the Posdunine type, that is

$$LBP = C \times \left[\frac{V}{V+2} \right]^2 \times \Delta^{1/3} \qquad \text{Eqn. 2.1}$$

Nevertheless if the deadmass/displacement ratio is assumed to be fairly constant, then the equation is equally true

$$LBP = C \times \left[\frac{V}{V+2} \right]^2 \times (DWT)^{1/3} \qquad \text{Eqn. 2.2}$$

This formula has been developed for further used in the design of offshore supply vessels in this study. Based on Fig. 2.5, it is observed that most of the vessels do have a value of C close to 7.86. Thus, the relationship between length, speed and deadmass can be written as

$$LBP = 7.86 \times \left[\frac{V}{V+2} \right]^2 \times (DWT)^{1/3} \qquad \text{Eqn. 2.3}$$

2.2 HULL FORM AND FORM COEFFICIENTS

The hull of an offshore supply vessel may be of either chine or rounded form. The chine hull was first adopted in early development to respond to demand for rapid delivery as it was simpler to construct. However rounded forms are now almost universal.

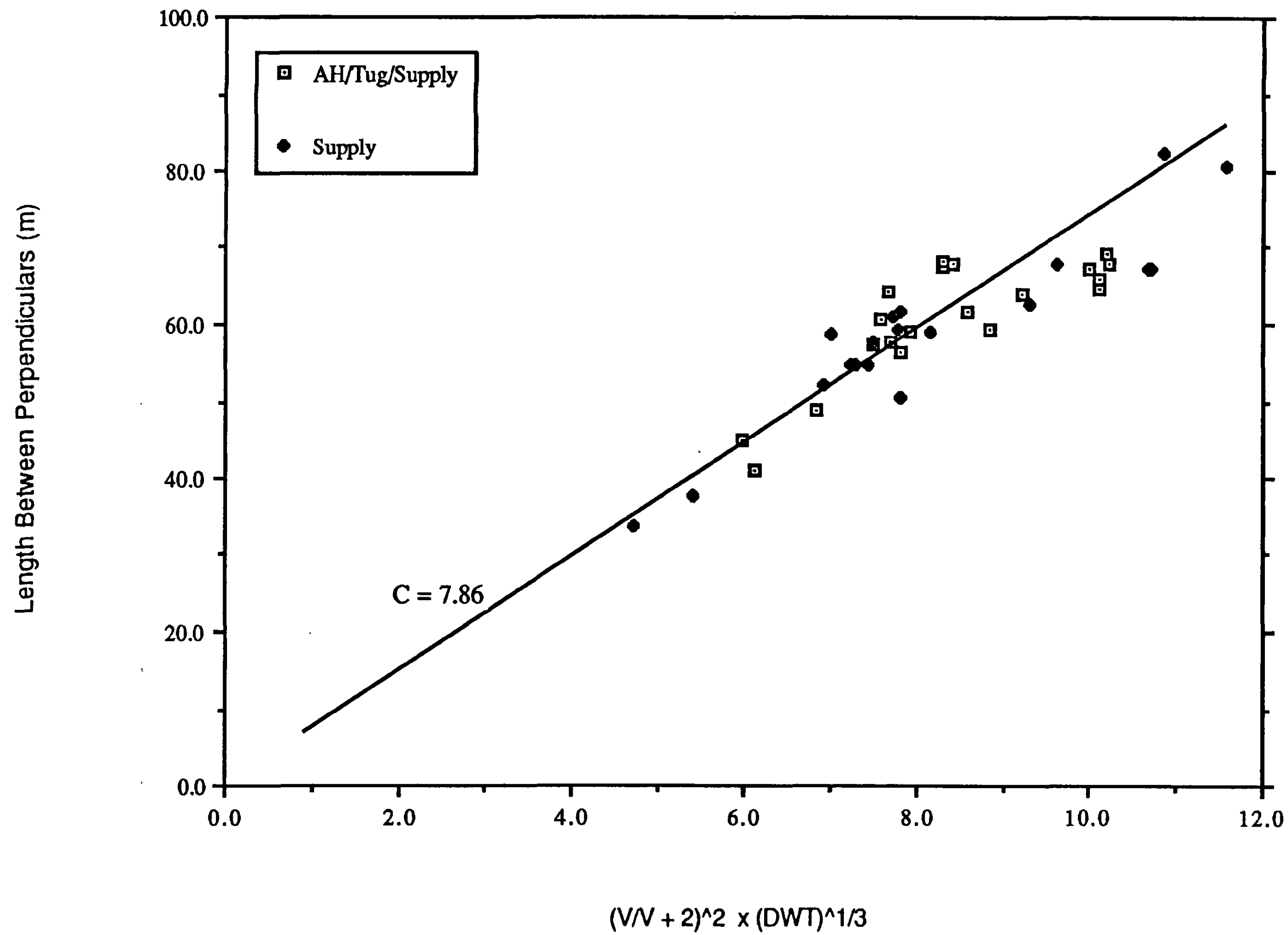


Fig. 2.5 Relation Between Length, Speed and Deadmass

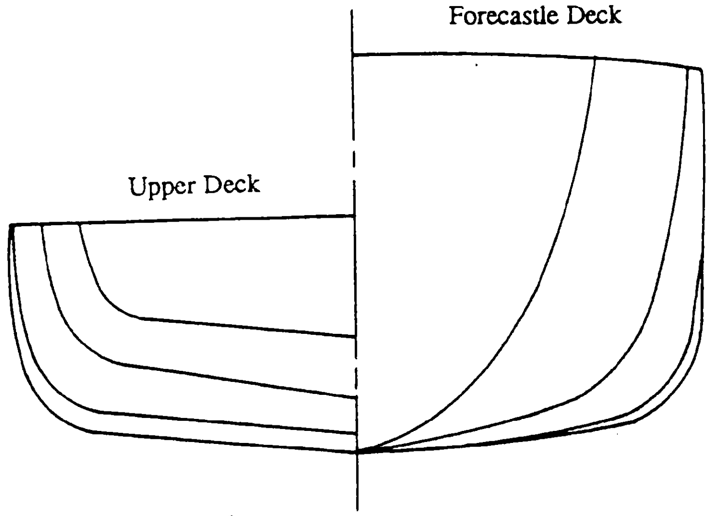


Fig. 2.6 Round Hull Design

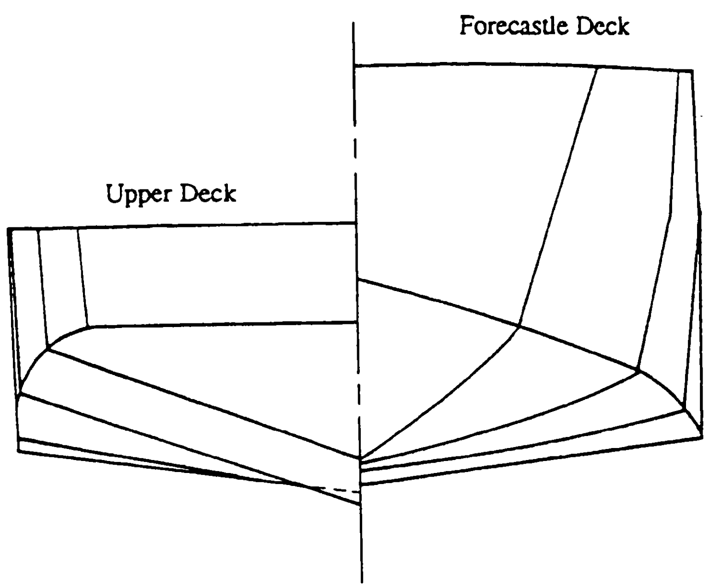


Fig. 2.7 Chine Hull Design

A main feature of the shape is the long and wide, open deck area aft and the tightly packed forecastle and forecastle deckhouses. Figures 2.6 and 2.7 illustrate the hull shape.

Figure 2.8 and 2.9 show the range of block coefficient for offshore supply vessels. Note the difference between most common values for pure supply vessels and for anchor handling/tug/supply vessels. In the latter type, a good supply of water to the propeller is essential resulting in a relatively low value of midship area coefficient and of longitudinal prismatic coefficient. The increased carriage of high mass density drilling fluids such as oil based mud means that deadmass is increasing in importance for pure supply vessels and is reflected by the values of block coefficient.

There are many relationships linking values of block coefficient to *Froude* number. A good one covering the full range of values of *Froude* number is given by *Watson* and *Gilfillan* [22]. Limiting *Froude* number to a particular type of vessel allows reasonable accuracy using linear relationships. Some of the simpler ones are given below which are reasonable for tugs and supply vessels.

(a) $C_B = 1.137 - 0.6\dfrac{V}{\sqrt{L}}$ [21] Eqn. 2.4

(b) $C_B = 1.0 - \frac{3}{8}(B/L + 1)\dfrac{V}{\sqrt{L}}$ [21] Eqn. 2.5

(c) $C_B = K - \dfrac{V}{3.62\sqrt{L}}$ where $K = 1.03$ to 1.15 [22] Eqn. 2.6

(d) $C_B = 0.821 L^{0.42} B^{-0.3072} T^{-0.1721} V^{-0.6135}$ [23] Eqn. 2.7

(e) $C_B = 0.7 + \frac{1}{8}\tan^{-1} 25(0.23 - \dfrac{V}{\sqrt{L}})$ [24] Eqn. 2.8

In this study, Eqn. 2.6 is adopted with value of K is 1.280 as it coincide with most values of block coefficient of the offshore supply vessels.

2.3 STABILITY OF OFFSHORE SUPPLY VESSELS

Stability requirements are given in full by IMO [31] and in part in section 2.3.2. The hullform of such vessels with its large values of beam/depth ratio has a tendency to immerse the upper deck edge at low angles of heel. Consequently the working draught is likely to be less than the maximum geometrical draught in order to maintain reasonable angles of upper deck edge immersion. Even then, the equivalent criteria given by IMO and stated in section 2.3.2 may have to be accepted.

Special minimum values of freeboard namely 0.005L must be maintained at the stern and allowances made for water trapped in pipes carried as deck cargo. Free surface effects must be carefully considered and anti rolling tanks must not compromise stability. Secure lashing of deck cargo is essential.

Modern offshore supply vessels have more superstructure and are less likely to have excessive GM but the greater variety of liquids transported means that fewer tanks are available for ballast.

Subdivision and damaged stability must also be considered but the requirements can generally be met by appropriate location of wing tank inner longitudinal boundaries and transverse bulkheads.

2.3.1 Existing Stability Criteria

While the history of vessel stability is extensive, the segregation of offshore supply vessels as a unique class of vessel requiring specific criteria was not addressed until after 1970. Listed below are some criteria that are most commonly mentioned.

US Coast Guard Weather [1]

$$GM_{req} = \frac{PAh}{\Delta \tan\theta} \qquad \text{Eqn. 2.9}$$

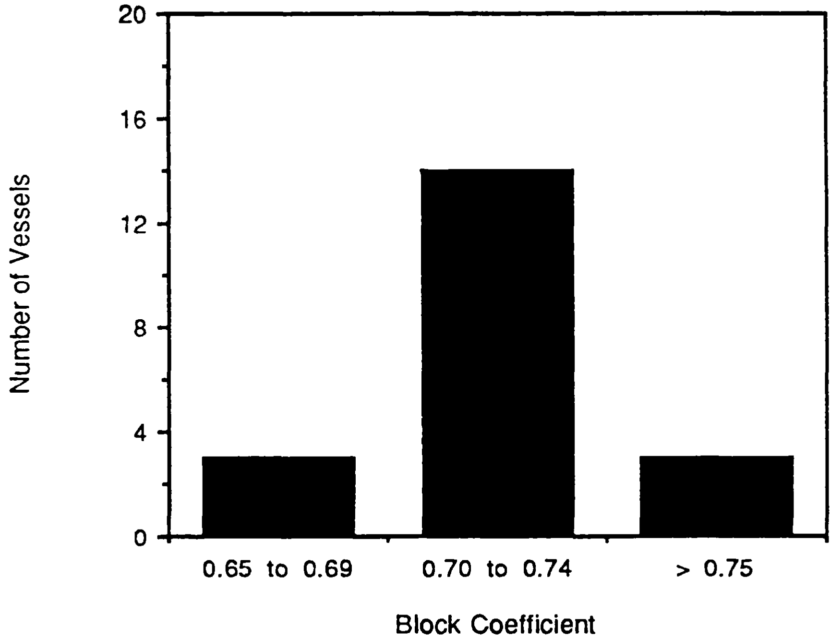


Fig. 2.8 Block Coefficient of Offshore Supply Vessels

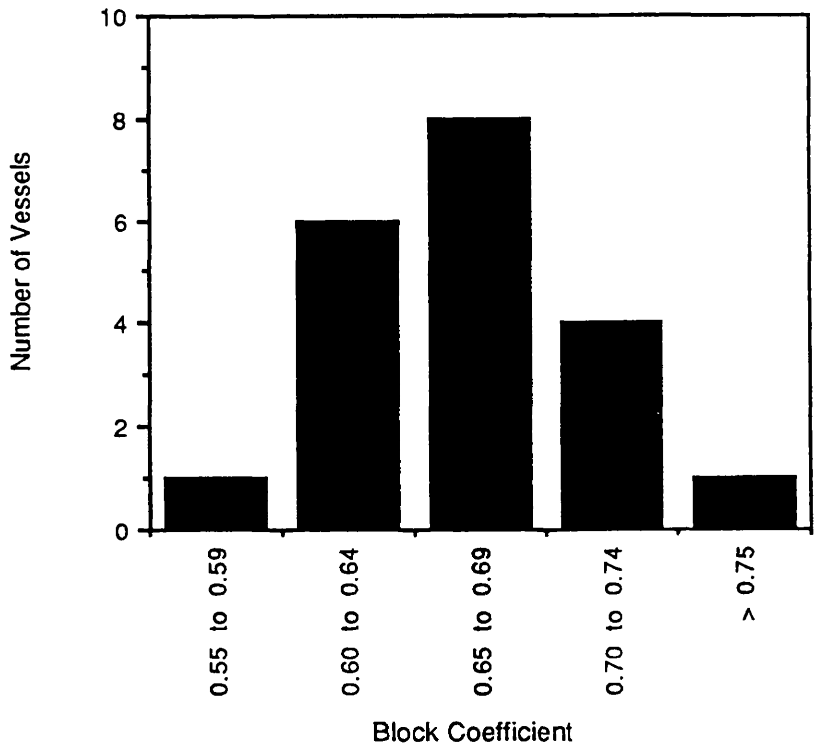


Fig. 2.9 Block Coefficient for Anchor Handling/Tug/Supply Vessels

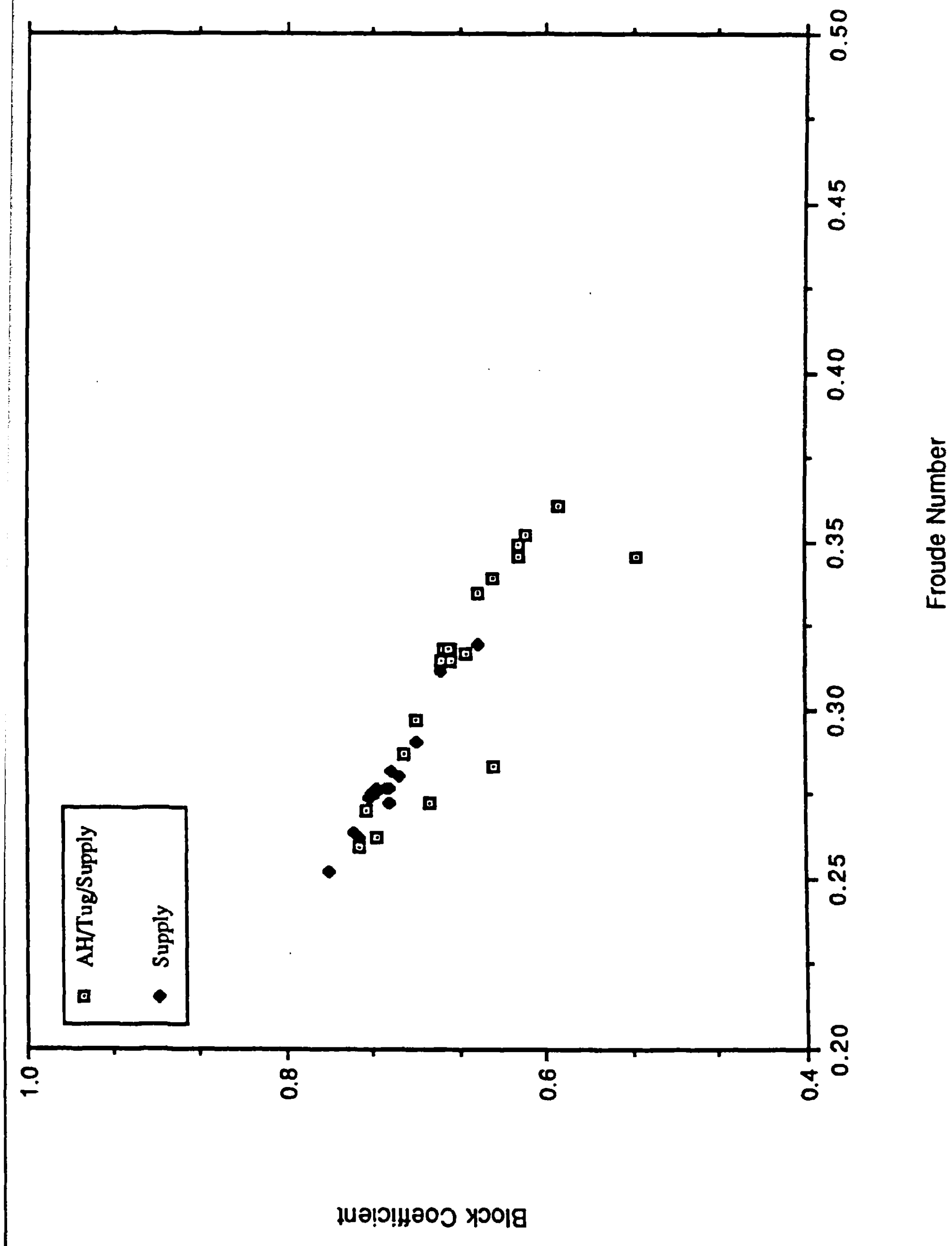


Fig. 2.10 Relation Between Block Coefficient and Froude Number

where

$P = 0.005 + (L/14{,}200)^2$ in ton/ft^2

A = projected lateral area above waterline in ft^2

h = vertical distance between centre of A and centre of underwater body in ft

$\tan\theta$ = angle to $\frac{1}{2}$ freeboard

Δ = displacement in tons

US Coast Guard Towline pull [1]

$$GM_{req} = \frac{N(P_S \times D)^{2/3} Sh}{38\Delta \times 2f / B} \qquad \text{Eqn. 2.10}$$

where

S = effective decimal fraction of propeller slipstream deflected by rudder assumed to fraction of propeller circle cylinder which would be intercepted by the rudder if turned 45°

h = vertical distance from propeller shaft centreline at rudder to towing bitts in ft

N = number of screws

B = moulded beam in ft

D = propeller diameter in ft

f = minimum freeboard in ft

Roach [4]

$$GM_{req} = \frac{P_B \times 15h}{\Delta f / B} \qquad \text{Eqn. 2.11}$$

where

h = vertical distance between centre of underwater body and towing bitts in ft

Δ = displacement in lbs

Argyriadis [6]

$$GM_{req} = \frac{P_S \times h}{100\Delta f / B} \qquad \text{Eqn. 2.12}$$

where

h, f, B and Δ are similar with Eqn. 2.10

Wood [6]

$$GM_{req} = \frac{(P_S \times D)^{2/3}\, h}{24\Delta f / B} \qquad \text{Eqn. 2.13}$$

where

h = vertical distance from propeller shaft centreline at rudder to towing bitts in ft

IMO [18]

(General vessels less than 100 m in length)

$GM \geq 0.15$ m

Some general comments may be made about these criteria. They are basically of two types, righting-energy criteria and required initial GM criteria, primarily based on power. The righting-energy criteria are generally applied to all types of offshore vessels as a mean of assessing the ability of the vessels to survive in waters subject to wind and sea. Criteria *US Coast Guard Towline Pull, Argyriadis,* and *Wood* are used for offshore supply vessels with towing function. Table 2.2 gives the comparison of various criteria with the actual GM of several existing vessels.

2.3.2 Range of Stability

It will be appreciated that GM alone does not tell the whole story so far as stability is concerned. An assessment has to be made as soon as possible of the range of stability, the maximum value of GZ and the angle at which it occurs.

IMO recommends [31] the normal ship criteria for stability namely :

a. The area under the righting lever curve (GZ curve) should not be less than 0.055 metre-radians up to $\theta = 30^o$ angle of heel and not less than 0.09 metre-radians up to $\theta = 40^o$ or the angle of flooding (θ_f) if this angle is less than 40^o. Additionally, the area under the righting lever curve (GZ curve) between the angles of heel of 30^o and 40^o or between 30^o and θ_f, if this angle is less than 40^o, should not be less than 0.03 metre-radians.

b. The righting lever (GZ) should be at least 0.20 m at an angle of heel equal or greater than 30^o

c. The maximum righting arm should occur at an angle of heel preferably exceeding 30^o but not less than 25^o.

d. The initial metacentric height GM_0 recommended shall not be less than 0.15 m.

The following equivalent criteria are used where an offshore supply vessel's characteristics render compliance with the above impracticable.

a. The area under the curve of righting levers (GZ curve) should not be less than 0.070 metre-radians up to an angle of 15^o when the maximum righting lever (GZ) occurs at 15^o and 0.055 metre-radians up to an angle of 30^o when the maximum righting lever (GZ) occurs at 30^o or above. Where the maximum righting lever (GZ) occurs at angle between 15^o and 30^o, the corresponding requisite area under the righting lever curve should be determined by use of the formula

$$\text{Area} = 0.055 + 0.001\,(30^o - \theta_{max})$$

b. The area under the righting lever curve (GZ curve) between the angles 30^o and 40^o or between 30^o and θ_{max} if this angle is less than 40^o, should not be less than 0.03 metre-radians.

Table 2.2 Comparison Between Various GM Criteria and Actual Values

VESSEL	LOA (m)	P_B	GM_{Act} (m)	GM_1 (m)	GM_2 (m)	GM_3 (m)	GM_4 (m)
Star Vega	68.00	5080.0	2.190	0.675	0.778	1.016	0.920
- na -	63.80	7200.0	2.485	0.510	0.702	1.750	0.860
- na -	65.20	8000.0	2.380	0.570	1.057	1.340	0.950
- na -	53.60	1700.0	2.160	0.384	0.630	0.818	0.630
- na -	50.30	2250.0	2.020	0.451	0.670	1.010	0.750

GM_1 = *US Coast Guard Towline Pull*

GM_2 = *Roach*

GM_3 = *Argyriadis*

GM_4 = *Wood*

c. The righting lever (GZ) should be at least 0.20 metres at an angle of heel equal to or greater than 30^o.

d. The maximum righting lever (GZ) should occur at an angle of heel not less than 15^o.

e. The initial transverse metacentric height (GM_0) should not be less than 0.15 metres.

2.3.3 Prediction of KN and GZ

A set of linear equations developed by Kupras and Majewski [29] is given in the form of diagrams for displacement force lever KN. This displacement force lever is expressed as a function of the ship's main particulars :

$$KN \sin\theta = \text{function } (B, T, D, W, CB)$$

where W is the mean sheer ((sheer aft + sheer forward)/2)

On the basis of the diagrams published by Kupras and Majewski, Kupras [30] carried out a regression analysis and the following relationship between the displacement force lever and the ship's main particulars was developed (see Fig. 2.11) :

$$KN_\theta = 1.025\ (A_1 + A_2 \times CB + A_3 \times \frac{W}{B} + A_4 \times \frac{D}{B} + A_5 \times \frac{B}{T}) \times \frac{B}{20} \qquad \text{Eqn. 2.14}$$

The sets of coefficients A_1 to A_5 are given in Table 2.3. Once the values of KN_θ are known, GZ at various angles of heel are calculated by

$$GZ = KN_\theta - KG \sin\theta \qquad \text{Eqn. 2.15}$$

Fig. 2.12 shows the comparison of GZ calculated with the above equation with actual values.

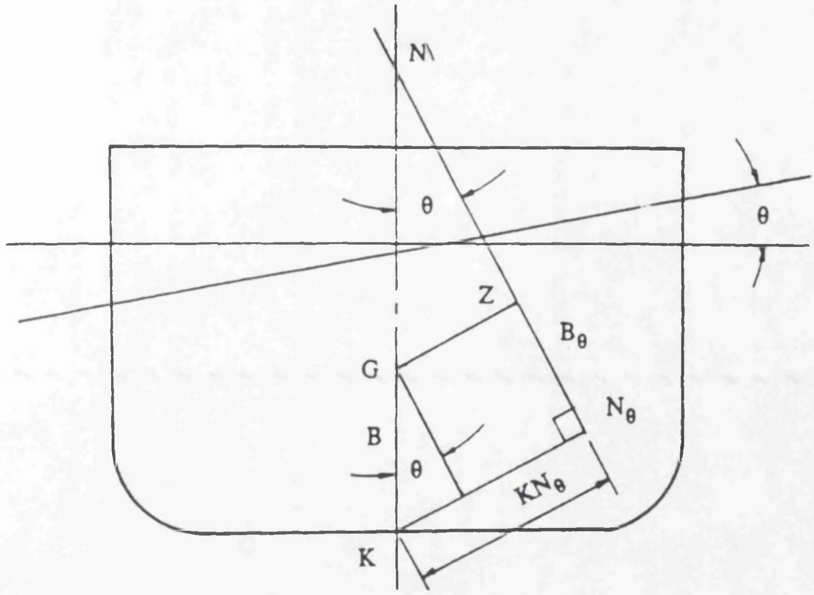
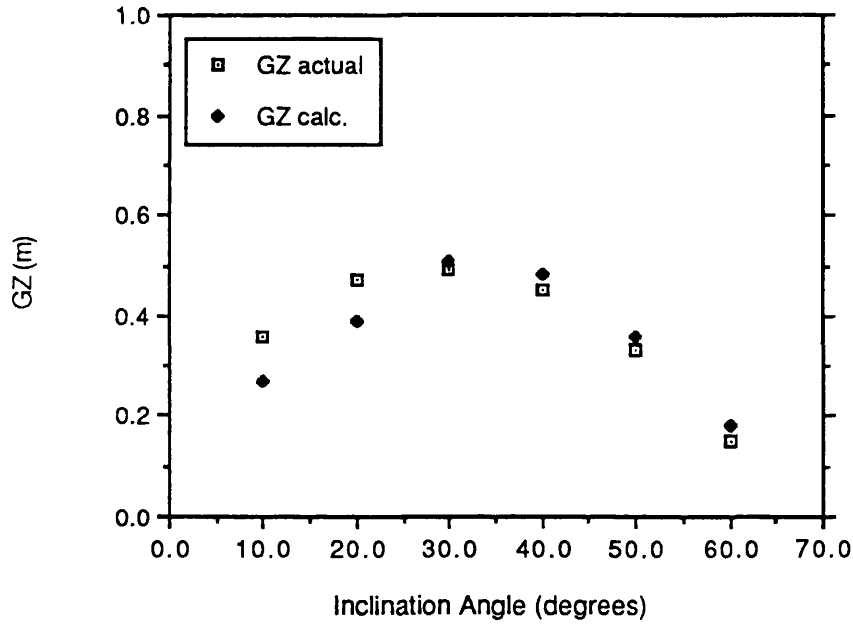


Fig. 2.11 Determination of KN_θ

Table 2.3 Values of Coefficients at Various Angles

θ (degrees)	Range	A_1	A_2	A_3	A_4	A_5
10	$D/B < 0.58$	0.0004			2.500	- 0.004
20		- 0.3050		0.1333	5.000	0.100
30		- 1.6410	0.1	0.6467	7.300	0.650
40		- 2.8150	- 0.2	1.1333	9.250	1.100
50		- 3.0358	- 0.3	1.6000	10.375	1.230
60		- 2.4045	- 0.5	2.0000	11.125	1.036
10	$0.58 \le D/B < 0.62$	0.6710			1.350	- 0.004
20		0.0876		0.1333	4.625	0.100
30		- 2.1920	- 0.1	0.6467	8.250	0.650
40		- 3.8300	- 0.2	1.1333	11.000	1.100
50		- 4.1925	- 0.3	1.6000	12.375	1.230
60		- 3.4920	- 0.5	2.0000	13.000	1.036
10	$D/B \ge 0.62$	1.0430			0.750	- 0.004
20		1.3385		0.1333	2.325	0.100
30		- 0.3010	- 0.1	0.6467	5.200	0.650
40		- 2.2800	- 0.2	1.1333	8.500	1.100
50		- 2.5525	- 0.3	1.6000	10.375	1.230
60		- 2.4070	- 0.5	2.0000	11.250	1.036



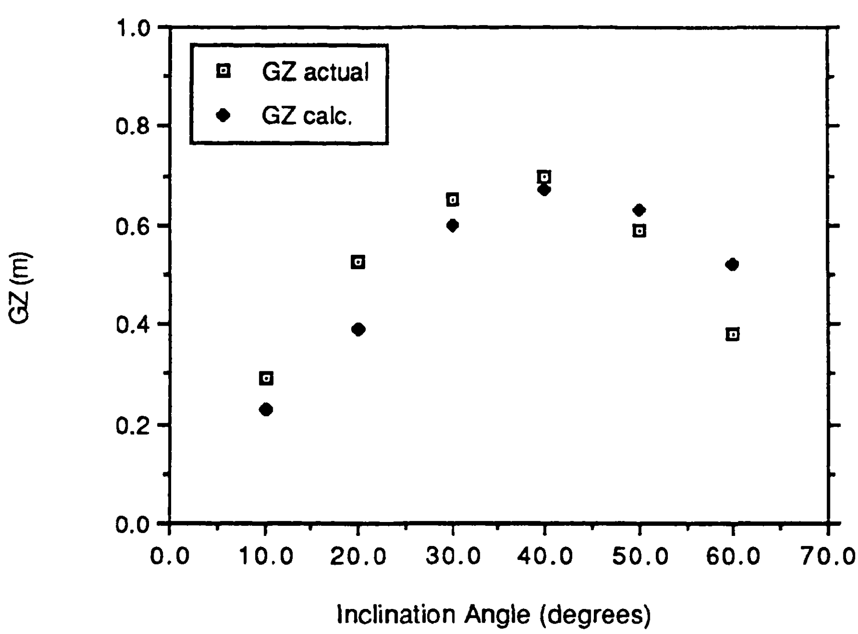


Fig. 2.12 Comparison Between Calculated and Actual GZ for Two Different Offshore Supply Vessels

2.4 STRUCTURAL DESIGN CONSIDERATIONS

This area requires approval by a Classification Society but normal ship design consideration apply in respect of longitudinal, transverse and local strength with particular additions in regions susceptable to damage. Such additions involve minimum thickness for bulkheads, side shell and the weather decks with deck cargo, the deckhouses on the forecastle deck and transverse framing at the fore end. The seatings of towing equipment must be adequate as must lashing arrangements for deck cargo. Generous freeing ports are required if solid bulwarks exist.

Figure 2.13 shows the section of a supply vessel while Table 2.4 shows typical scantling of pure supply and anchor handling/tug/supply vessels.

2.5 TONNAGE

An assessment of the gross tonnage of ship is early required in the design in order to estimate the statutory requirements for the lifesaving appliances and dues. Study of forty existing vessels shows that an empirical relationship may be established between length x breadth x depth and gross tonnage as shown in Fig. 2.14 where

Gross Tonnage = 0.24 LBD tonne　　　Eqn. 2.16

The ratio of net tonnage to gross tonnage varies as may be expected with the details of the designs. An average value, as can be seen from Fig. 2.15, is

Net Tonnage = 0.36 Gross Tonnage　　　Eqn. 2.17

2.6 CONCLUSION

This study has established trends in several design aspects of the offshore supply vessels in particular the pure supply and the anchor handling/tug/supply vessels. They have been presented in a form useful in all phases of offshore supply industry. Subjects such as hull form and stability are discussed in detail as these factors have always been the main province of naval architects.

To date, the continuous demand for growth in size, powering requirements have been met by steady development of new buildings. As long as the offshore oil industry is continuing, the demand for such vessels will continue.

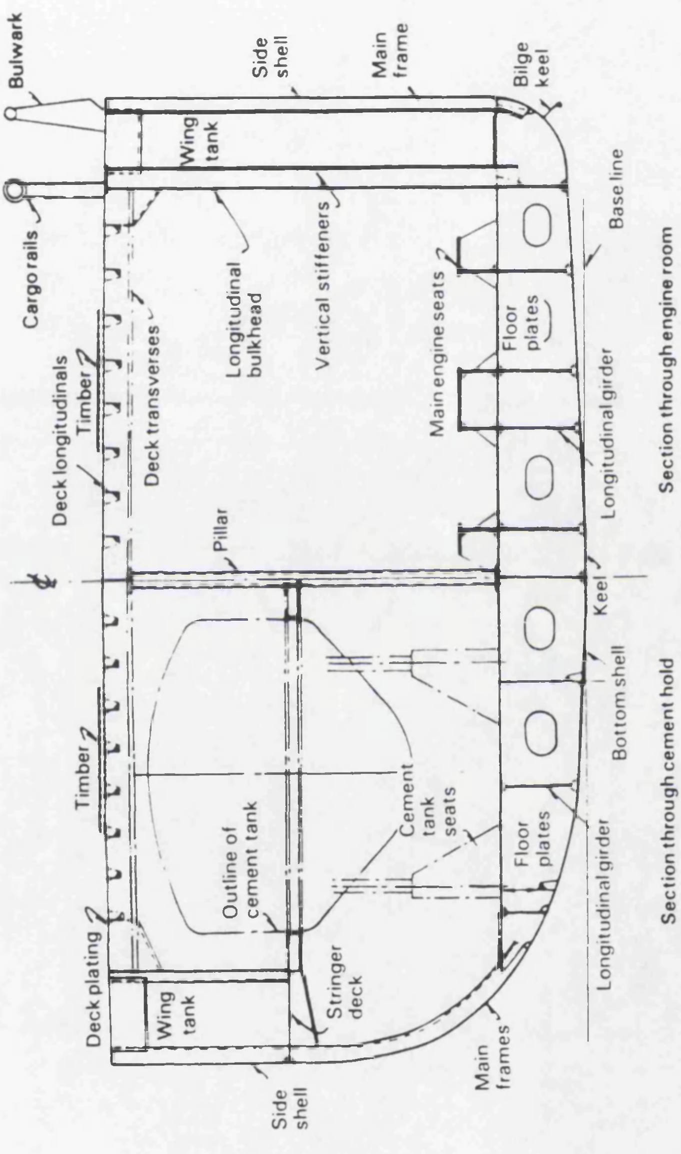


Fig. 2.13 Typical Pure Supply Vessel Sectional View [27]

Table 2.4 Typical Scantlings for Pure Supply and AH/Tug/Supply Vessels

MAIN DIMENSIONS	SUPPLY	AH/TUG/SUPPLY
Length Overall	55.27 m	68.70 m
Length Bet. Perp.	55.00 m	58.50 m
Breadth Moulded	11.60 m	13.70 m
Depth Moulded	4.65 m	6.75 m
Draught	3.86 m	5.00 m
PLATE SCANTLING	**mm**	**mm**
Keel	11.00	12.00
Shell Bottom	10.00	10.00
Shell Side	8.50	8.50
Sheerstrake	8.50	9.50
Bulwark	6.00	9.50
Double Bottom Floor	9.50	8.50
Double Bottom Girder	10.00	11.00
Tank Top	7.00	8.50
Main Bulkheads	6.50 - 8.00	6.50 - 8.00
Main Deck	7.00	9.50
SECTION SCANTLING	**mm**	**mm**
Main Frames (bulb plates)	152 x 9.5	200 x 10.0
Main Deck Long. (bulb plate)	127 x 7.1	160 x 7.5
Deck Transverse (web)	324 x 13.2 BP	370 x 14.0 BP
Main Bulkhead Stiffeners	178 x 10.5	260 x 10.0

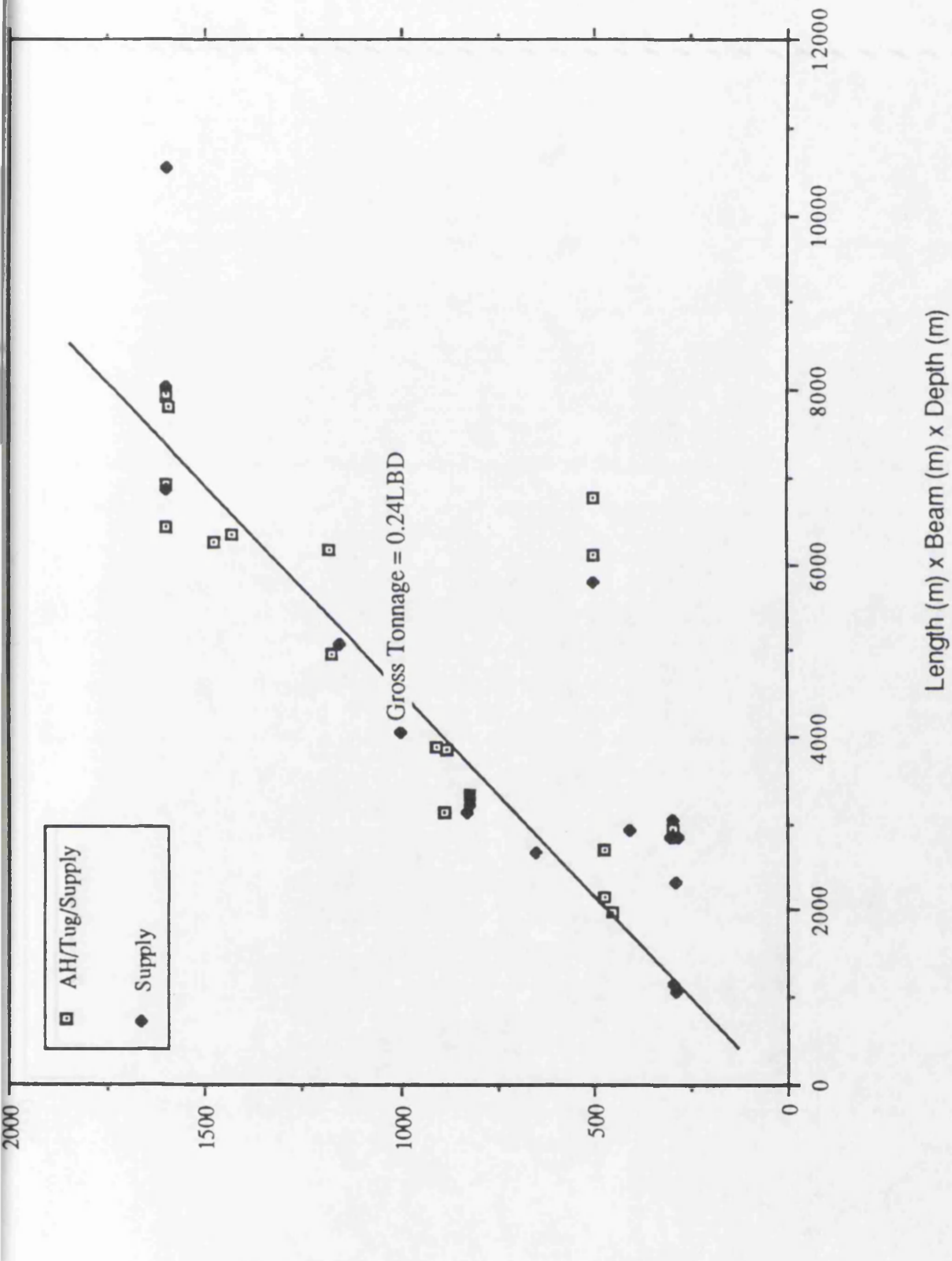


Fig. 2.14 Relation Between Gross Tonnage and LBD

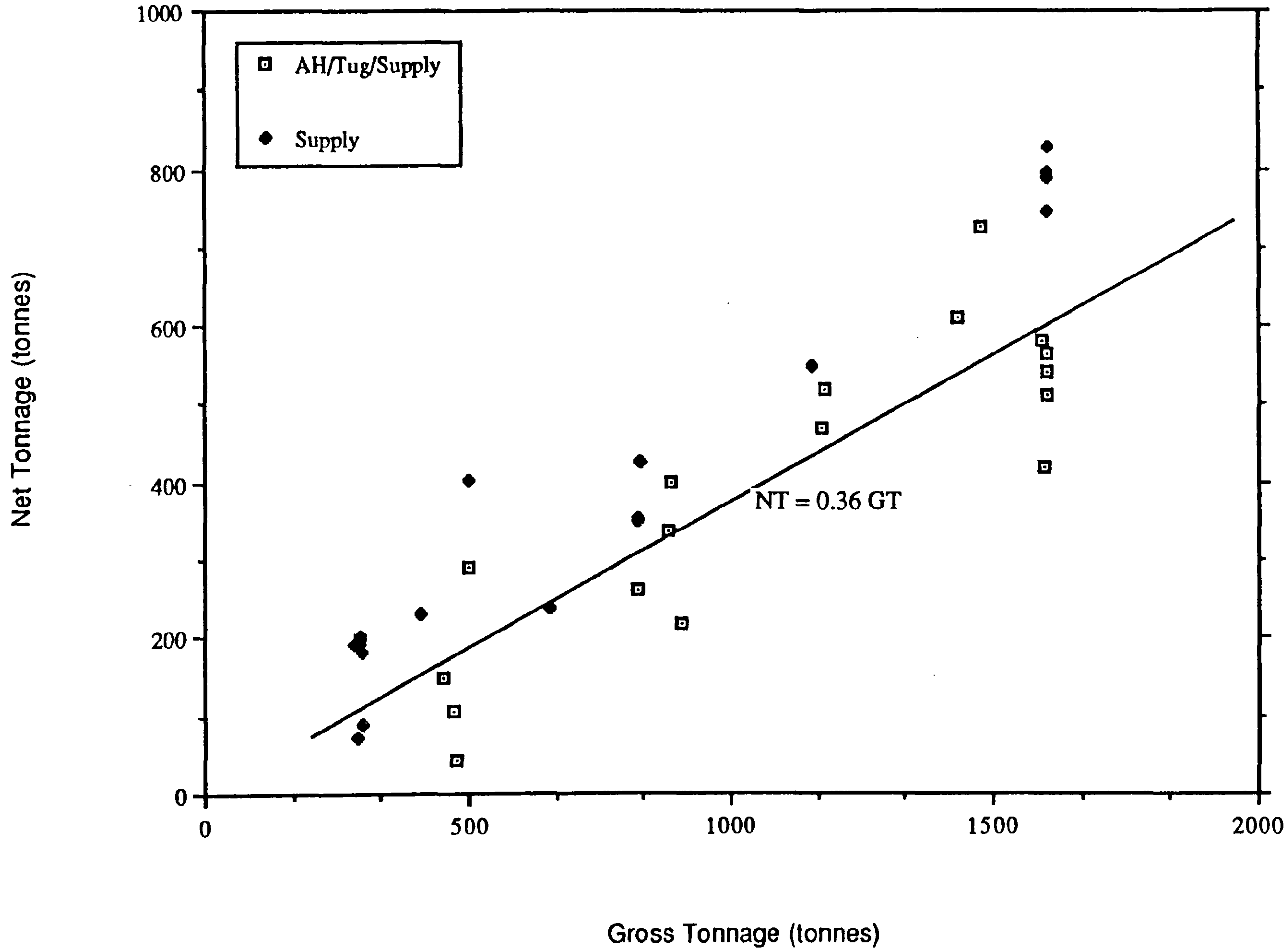


Fig. 2.15 Relation Between Net Tonnage and Gross Tonnage

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CHAPTER 3

MASS AND CAPACITY ESTIMATION

CHAPTER 3

MASS AND CAPACITY ESTIMATION

3.0 INTRODUCTION

Having analysed the main parameters, the next step in preliminary design is the estimation of lightship mass and capacity. Although the estimation of the lightship mass and capacity is approximated using well developed empirical formula, care has to be taken so that these estimations do not go far beyond the values of a similar existing vessel. Mistakes in such estimation may result in a reduction in the cargo deadmass of the vessel.

The lightship mass is composed of steel mass, outfit mass, machinery mass, deck machinery and margin on lightship mass. The following subsections deal with methods of estimating each of these masses.

There are several factors affecting the lightship mass of the offshore supply vessels. Among these factors are :

a. deadmass target limits the designer worked with during the design phase of the vessel,

b. if the vessel has a raised forecastle (almost all supply vessels do),

c. machinery installations,

d. block coefficient,

e. ice classification,

f. size of superstructures,

g. capability of carrying high density liquid cargoes

h. size and number of bulk mud tanks, and

i. propeller shrouds.

3.1 STEEL MASS

The steel mass is the most significant percentage of the total lightship mass, and as such, it is essential that an accurate mass be estimated. Additionally, the construction cost of the ship is also related to the steel mass.

There are numerous methods available for calculating the net steel mass. Most of the methods or formulae are derived by the application of regression analysis on existing ships data and indices alloted to the various dimensions such as length, breadth, depth, draft and block coefficient. These indices vary widely depending on the influence of each of the dimensions.

The methods presented in this study are selected from various papers to calculate the steel mass of offshore supply vessels. Even though some of the methods were not originally used for estimating steel mass of such vessels, nevertheless it is worth using them for comparison.

a. *Benford* [15]

$$W_S = 8407\left[\frac{LBD / 100}{1000}\right]^{0.9} \text{ x } (0.675 + (CB/2)) \text{ x}$$

$$\left[0.00585 \text{ x}\left[\frac{L}{D} - 8.3\right]^{1.8} + 0.939\right] \text{ x}\left[0.36\left[\frac{L_s}{LBP}\right]\right] \quad \text{Eqn. 3.1}$$

where L_S is the length of superstructure.

b. *Watson* [12]

$$W_S = KE^{1.36}\,[1 + 0.5(C_{B'} - 0.70) \quad \text{Eqn. 3.2}$$

where

$E = L(B + T) + 0.85 \text{ x } L(D - T)$ + allowances for superstructures and deckhouses

$C_{B'} = C_B + (1 - C_B)\dfrac{(0.8D - T)}{3T}$ and

$K = 0.041$ to 0.051 for $800 < E < 1300$

c. *Caldwell* [16]

$$W_S = \frac{0.44 \times LBD}{100} \times \sqrt{\frac{L/D}{8}} \times [1 + 0.05\,(CB - 0.5)] \qquad \text{Eqn. 3.3}$$

where L, B and D are in ft.

d. *Simpson* [17]

$$W_S = LBD \times 0.003 \qquad \text{Eqn. 3.4}$$

where L, B and D are in ft.

e. *Harvald* and *Jensen* [18]

$$W_S = 0.120 \times LBD \qquad \text{Eqn. 3.5}$$

f. *Meredith* [1]

$$W_S = LBP \times B \times D \times 93.44 \times 10^{-3} \qquad \text{Eqn. 3.6}$$

Comparison between the various methods of evaluating the steel mass of offshore supply vessels with actual values are given in Table 3.1. The equation given by *Watson* seems to suit the estimation of steel mass of the offshore supply vessels. Although, those equation given by *Caldwell*, *Simpson* and *Meredith* were developed for such vessels, the estimations are poor. This may be due to the fact that those equation developed by *Caldwell* and *Simpson* are outdated while *Meredith*'s equation was developed based on a single offshore supply vessel although demarcation problems for the allocation of individual items will also be present.

Table 3.1 Comparison of Different Methods of Calculating Steel Mass and Actual Values

Name of Vessel	Actual Steel Mass (t)	Benford		Watson		Caldwell		Simpson		Harvald/Jensen		Meredith	
		(t)	% diff.	(t)	% diff.	(t)	% diff.	(t)	% diff.	(t)	% diff.	(t)	% diff.
Seaforth Jarl	692.0	708.0	+ 2.3	743.0	+ 7.3	931.0	+ 34.5	667.0	- 3.0	744.0	+ 7.5	598.0	- 13.5
Seaforth Earl	490.0	427.0	- 12.9	440.0	- 10.2	528.0	+ 7.8	362.0	- 26.1	403.0	- 17.8	313.0	- 36.1
Lundy Shore	550.0	353.0	- 35.8	513.0	- 6.7	570.0	+ 3.6	315.0	- 42.7	380.0	- 30.9	274.0	- 50.2
Star Vega	840.0	486.0	- 42.1	796.0	- 5.2	913.0	+ 8.7	449.0	- 46.5	500.0	- 40.4	390.0	- 53.5
Stirling Esk	708.0	645.0	- 8.9	714.0	+ 0.9	1041.0	+ 47.8	604.0	- 14.7	684.0	- 3.4	474.0	- 33.0
Stirling Teal	469.0	418.0	- 10.9	474.0	+ 1.1	676.0	+ 44.1	355.0	- 24.3	400.0	- 14.7	288.0	- 38.6
*	1065.0	761.0	- 28.5	980.0	- 8.0	943.0	- 11.5	757.0	- 28.9	819.0	- 23.1	556.0	- 47.8
**	750.0	733.0	- 2.3	762.0	+ 1.6	1052.0	+ 40.2	682.0	- 9.0	716.0	+ 1.5	507.0	- 32.4

(*/** - Name Not Available)

In this application the value of E is not increased to allow for the important effect of the forecastle. Provided the effect of the forecastle is similar among offshore supply vessels, it can be absorbed in the choice of K.

3.2 OUTFIT AND HULL ENGINEERING MASS

Outfit mass contains many items and will reflect the specification and the purpose of the ship. There can be wide variation of the mass items recorded in two different shipyards because of the differences in accounting procedures in respect of subcontract jobs. It may be recorded as material cost and a labour cost for fitting. The best procedure at the preliminary design stage is to ascertain the outfit mass from a basis ship item by item and proportion outfit mass in relation to the square number of length x breadth.

Various methods suggested over the years for preliminary ship design are considered here. A comparative evaluation of the different methods is then carried out and then the method used in this study is given.

a. *Watson* [12]

$$W_O = 0.23 \times L \times B \qquad \text{Eqn. 3.7}$$

b. *Katsoulis* [20]

$$W_O = kL^{1.3}B^{0.8}D^{0.3} \qquad \text{Eqn. 3.8}$$

where k = 0.045 to 0.065

c. *Simpson* [17]

$$W_O = LBD \times 0.001 \qquad \text{Eqn. 3.9}$$

where L, B and D are in ft.

d. *Erichsen* [19]

$$W_O = 140.21(CN/1000)^{0.825} \qquad \text{Eqn. 3.10}$$

where CN = LBD/100

e. *Meredith* [1]

$$W_O = 163.6 \times L \times B \times 10^{-6} \qquad \text{Eqn. 3.11}$$

f. *Caldwell* [17]

$$W_O = L \times B/73 \qquad \text{Eqn. 3.12}$$

where L and B are in ft.

Comparison between various methods of evaluating the outfit mass of offshore supply vessels with actual values are given in Table 3.2. The equation given by *Watson* and *Katsoulis* seems to suit the estimation of outfit mass of offshore supply vessels. In this study, only the equation developed by *Watson* will be used.

3.3 MACHINERY MASS

Offshore supply vessels are complex mechanically, all having more than one propeller and one or more thrusters. Attempts at simplification have not been acceptable to the industry. The most frequently adopted arrangement is for two main engines, driving either a twin-input/single output gearbox or twin screws. Alternatively, a twin-screw installation may be arranged by having four engines in two banks, each pair driving into a twin-input/single-output gearbox. Although the capital outlay is higher per unit power, the obvious advantages of the multi-engin e installation are the flexibility of

Table 3.2 Comparison of Different Methods of Calculating Outfit Mass and Actual Values

Name of Vessel	Actual Outfit Mass (t)	Watson		Katsoulis		Simpson		Erichson		Meredith		Caldwell	
		(t)	% diff.	(t)	% diff.	(t)	% diff.	(t)	% diff.	(t)	% diff.	(t)	% diff.
Seaforth Jarl	200.0	211.0	+ 5.5	221.0	+10.5	222.0	+ 11.0	267.0	+ 33.5	151.0	- 24.5	136.0	- 32.0
Seaforth Earl	158.0	149.0	- 5.7	139.0	- 12.0	120.0	- 24.0	162.0	+ 2.5	106.0	- 32.9	97.0	- 38.6
Lundy Shore	137.0	140.0	+ 2.2	131.0	- 4.4	114.0	- 16.8	154.0	+ 12.4	100.0	- 27.0	91.0	- 33.6
Star Vega	210.0	202.0	- 3.8	194.0	- 7.6	170.0	- 19.0	208.0	- 1.0	144.0	- 31.4	131.0	- 37.6
Stirling Esk	205.0	210.0	+ 2.4	213.0	+ 3.9	205.0	0.0	250.0	+ 22.0	150.0	- 26.8	137.0	- 33.2
Stirling Teal	172.0	165.0	- 4.1	156.0	- 9.4	120.0	- 30.0	160.0	- 7.0	118.0	- 31.4	107.0	- 37.8
*	216.0	224.0	+ 3.7	231.0	+ 6.9	245.0	+ 13.4	290.0	+ 34.2	160.0	- 25.9	146.0	- 32.4
**	208.0	205.0	- 1.4	215.0	+ 3.4	228.0	+ 9.6	273.0	+ 31.3	146.0	- 29.8	131.0	- 37.0

(*/** - Name Not Available)

cruising speed, reduced consumption and maintenance at sea, using the minimum number of prime mover but always at their best efficiency.

There are various distinctive methods of evaluating the machinery mass of ships in the preliminary design stage and some of these are considered in this study. A comparison between these equations with actual machinery mass of offshore supply vessels is done.

a. *Meredith* [1]

$$W_M = (62.63 \times P_B) \times 10^{-3} \qquad \text{Eqn. 3.13}$$

b. *Watson* [12]

$$W_M = 0.16\,(P_B)^{0.89} \qquad \text{Eqn. 3.14}$$

c. *Barrass* [12]

$$W_M = \frac{P_B}{18} + 300 \qquad \text{Eqn. 3.15}$$

d. *Caldwell* [17]

$$W_M = P_B/16 \qquad \text{Eqn. 3.16}$$

Comparison between the various methods of evaluating the machinery mass of offshore supply vessels with actual values are given in Table 3.3. From this table, it is noted that the equation given by *Barrass* seems to over estimate while that of *Meredith* and *Caldwell* (despite originally used for offshore supply vessel design) seems to under estimate the machinery mass. Though the equation given by *Watson* was intended for only steam turbine machinery, the results given by such equation were found to be satisfactory. Thus, the equation used in this study to evaluate the machinery mass will be the one developed by *Watson*.

Table 3.3 Comparison of Different Methods of Calculating Machinery Mass and Actual Values

Name of Vessel	Power (BP)	Actual Machinery Mass (t)	Meredith		Watson		Barass		Caldwell	
			(t)	% diff.	(t)	% diff.	(t)	% diff.	(t)	% diff.
Seaforth Jarl	3600	270.0	226.0	- 16.2	234.0	- 13.3	500.0	+ 85.0	225.0	- 16.7
Seaforth Earl	2000	165.0	125.0	- 24.2	140.0	- 15.1	411.0	+149.0	125.0	- 24.2
Lundy Shore	5600	325.0	351.0	+ 0.8	346.0	+ 6.5	611.0	+ 88.0	350.0	+ 7.7
Star Vega	5080	318.0	318.0	0.0	318.0	0.0	582.0	+ 83.0	318.0	0.0
Stirling Esk	2600	192.0	162.0	- 15.6	175.0	- 8.8	445.0	+132.0	163.0	- 15.1
Stirling Teal	3200	230.0	200.0	- 13.1	211.0	- 8.2	478.0	+107.0	200.0	- 13.0
*	8000	488.0	501.0	+ 2.7	476.0	- 2.4	745.0	+ 52.0	500.0	+ 2.4
**	7200	440.0	451.0	+ 2.5	433.0	- 1.6	700.0	+ 75.0	450.0	+ 2.2

(*/** - Name Not Available)

3.4 DEADMASS

Offshore supply vessels are increasingly deadmass carriers with heavier muds coming into favour although the working deadmass may be associated with a draught less than the maximum geometrical draught for stability reasons. The components of deadmass will vary depending on the purpose and service of the vessel but can be approximated from Fig. 3.1 by

$$\text{LBD m}^3 = (3 \times \text{Deadmass}) \text{ tonnes} \qquad \text{Eqn. 3.17}$$

3.5 CAPACITY

With regard to offshore supply vessels, capacity estimation should be divided into two main categories that is the deck cargo capacity and the underdeck capacity.

3.5.1 Deck Cargo Capacity

Offshore supply vessels are single-deck vessels with the forecastle and deckhouses placed well forward, thereby devoting the after deck approximately two thirds of the main deck to deck cargo space. They are capable of carrying large quantities of drill pipe, casing, pipe and other heavy, bulky items of oil field equipment. The principal factors affecting the maximum allowable deck cargo capacity of such vessels, assuming constant vertical centre of gravity above deck, include :

a. lightship KG and deadmass of vessel,

b. extent of deck casings and trunks,

c. beam/depth and length/beam ratios of vessel,

d. block coefficient of hull,

e. height of chine bar,

f. optimisation of tank arrangement during planning stages with a view to achieve the maximum allowable deck cargo at full load waterline.

Figure 3.2 shows the relationship between deck cargo area and maximum allowable deck cargo for offshore supply vessels.

3.5.2 Underdeck Capacity

The principal payload of an offshore supply vessel includes the total amount of supplies it can carry under the main deck and the capacity and versatility of stowage arrangements. Figure 3.3 shows the relationship between cubic number and total underdeck capacity.

The total underdeck payload is a representative figure which is the cumulative sum of all cubic spaces in the hull utilised, and directly affects the utility and carrying capability of the vessel. Thus they include :

a. total fuel oil/base oil for rig,
b. total dry hopper tanks capacity (mud/cement),
c. total drill water capacity,
d. total ballast capacity,
e. total capacity for other drilling fluids,
f. total potable water,
g. total capacity utilised for rig chain, and
i. sludge tank capacity.

However, there are certain limitations which affect the underdeck capacity such as the block coefficient of the hull at upper deck level, size of main and auxiliary engines dictating the size of the engine room and other machinery spaces, stability tanks (where fitted), size of passageways and other non-usable spaces and voids, size of steering compartment, and size of the vessel's chain lockers.

Figures 3.4, 3.5, 3.6 and 3.7 show the capacity of cargo fuel, drilling water, potable water and mud/cement against the total underdeck capacity of forty offshore supply vessels. From these graphs, it may conclude that the typical breakdown of an offshore supply vessel are as follows :

a. capacity of cargo fuel is 0.25 to 0.30 of total underdeck capacity,

b. capacity of drilling water is 0.2 to 0.30 of total underdeck capacity,

c. capacity of potable water is 0.05 to 0.20 of total underdeck capacity, and

d. capacity of mud and cement is 0.15 to 0.25 of total underdeck capacity.

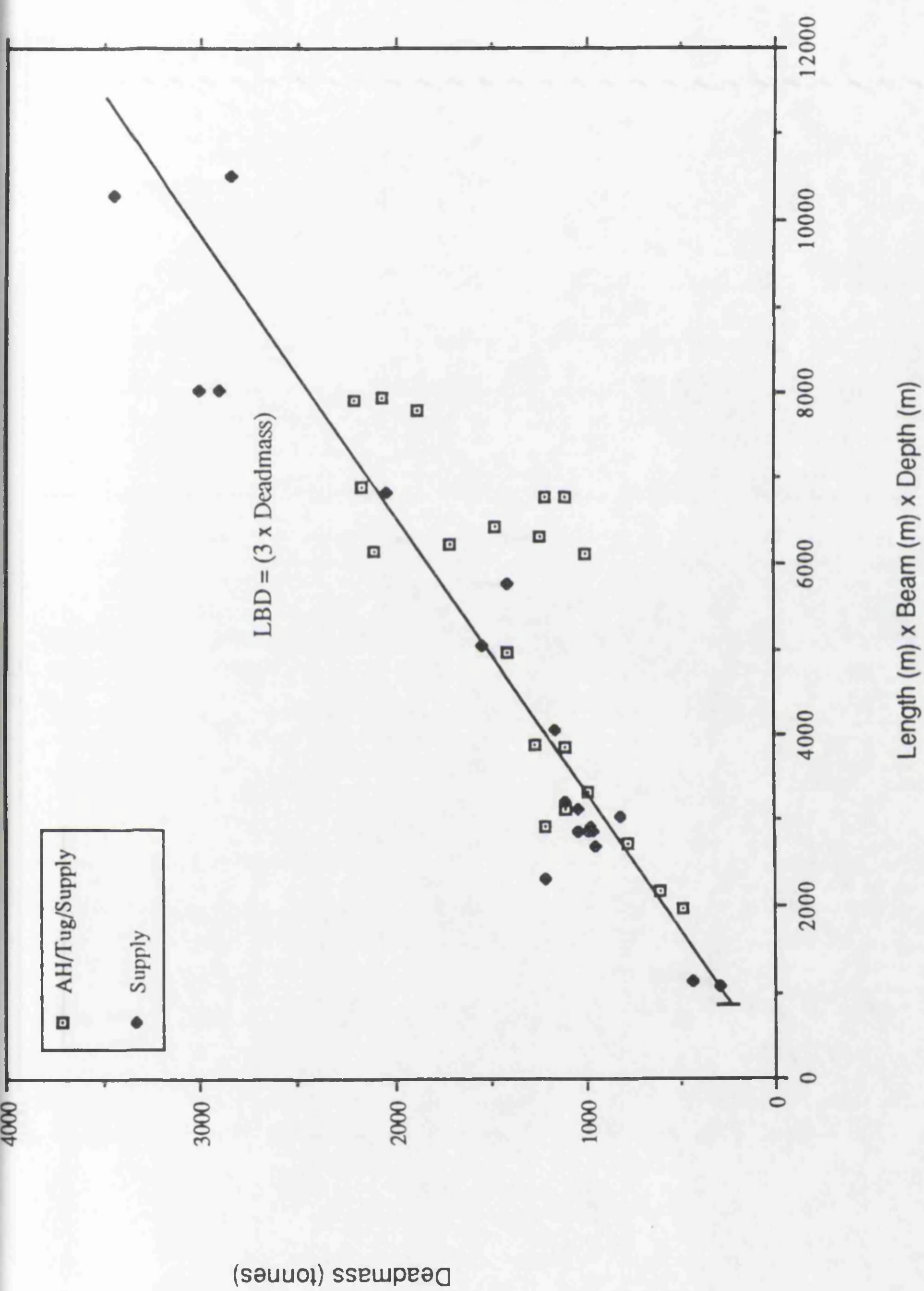

Fig. 3.1 Relation Between Deadmass and LBD

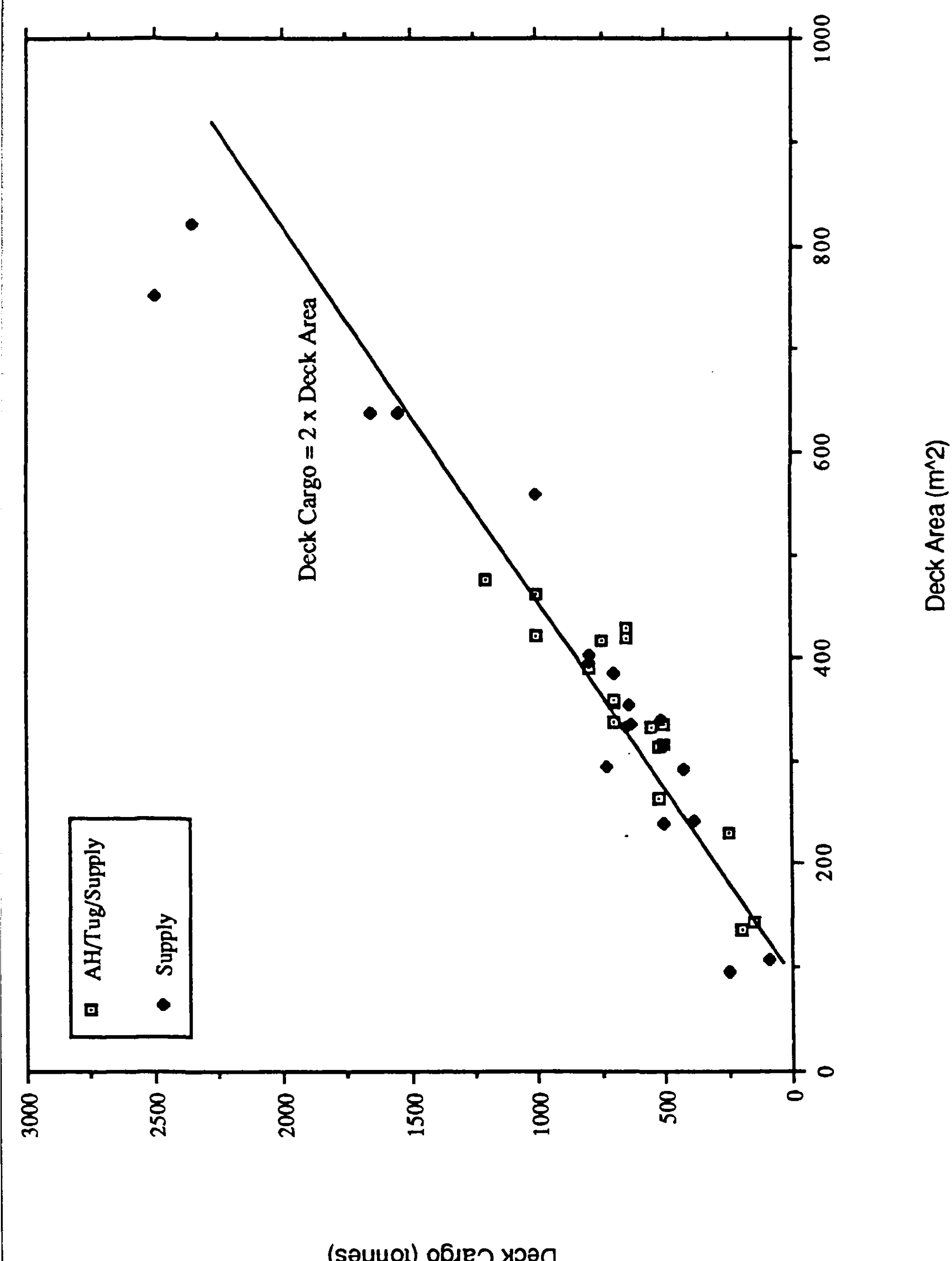

Fig. 3.2 Relation Between Maximum Deck Cargo and Deck Area

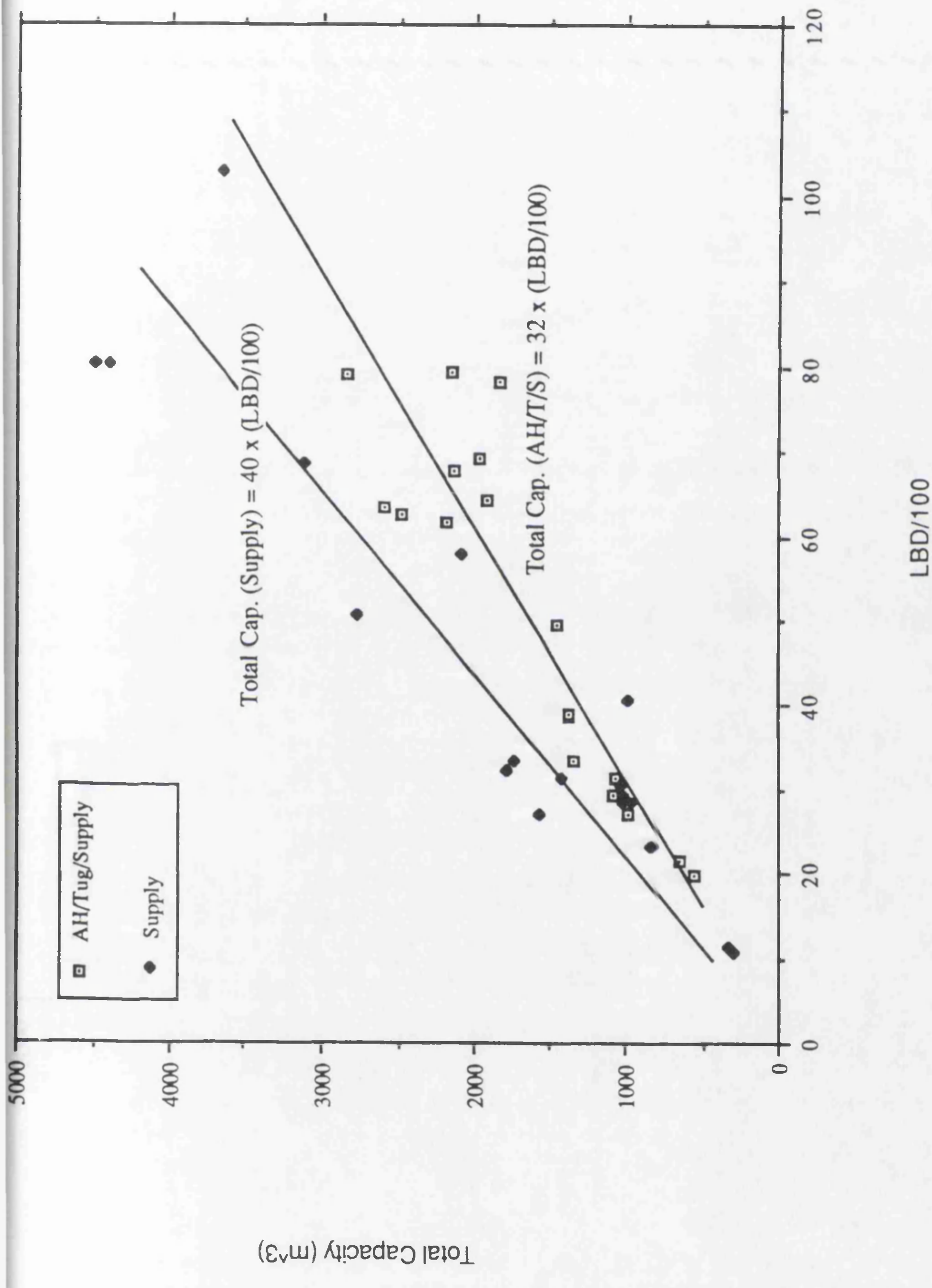

Fig. 3.3 Relation Between Total Underdeck Capacity and Cubic Number

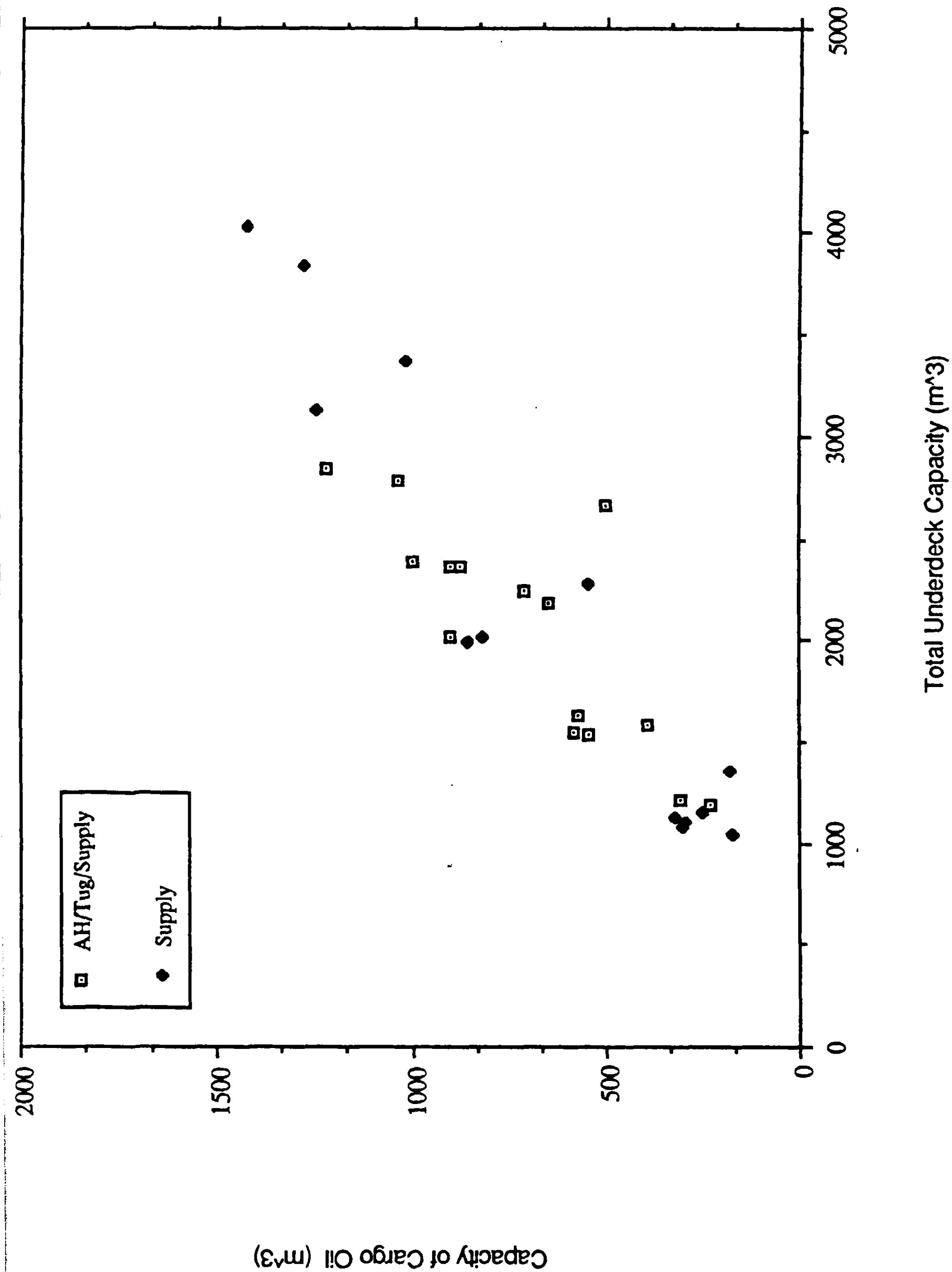

Fig. 3.4 Relation Between Capacity of Cargo Oil and Total Underdeck Capacity

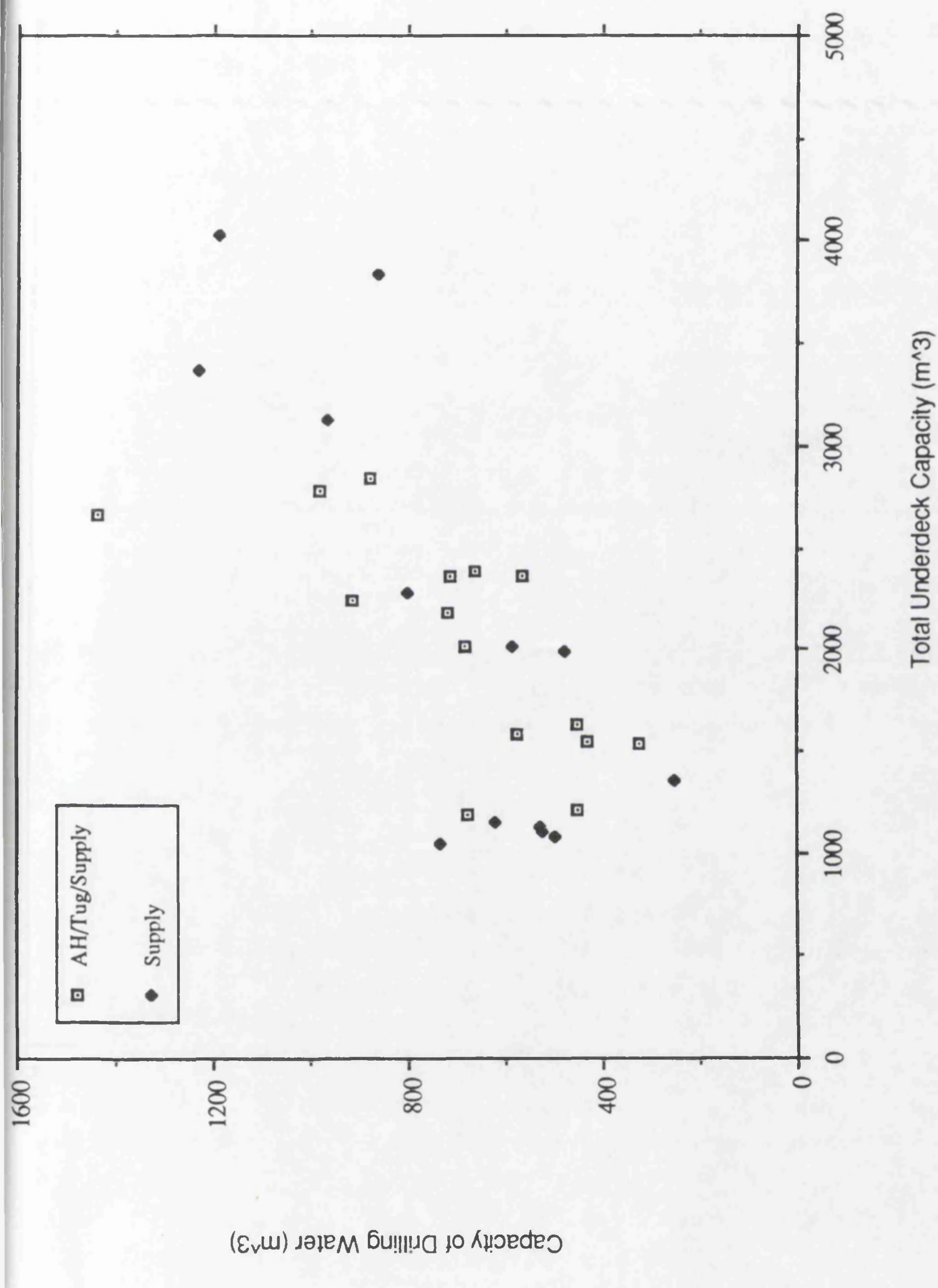

Fig. 3.5 Relation Between Capacity of Drilling Water and Total Underdeck Capacity

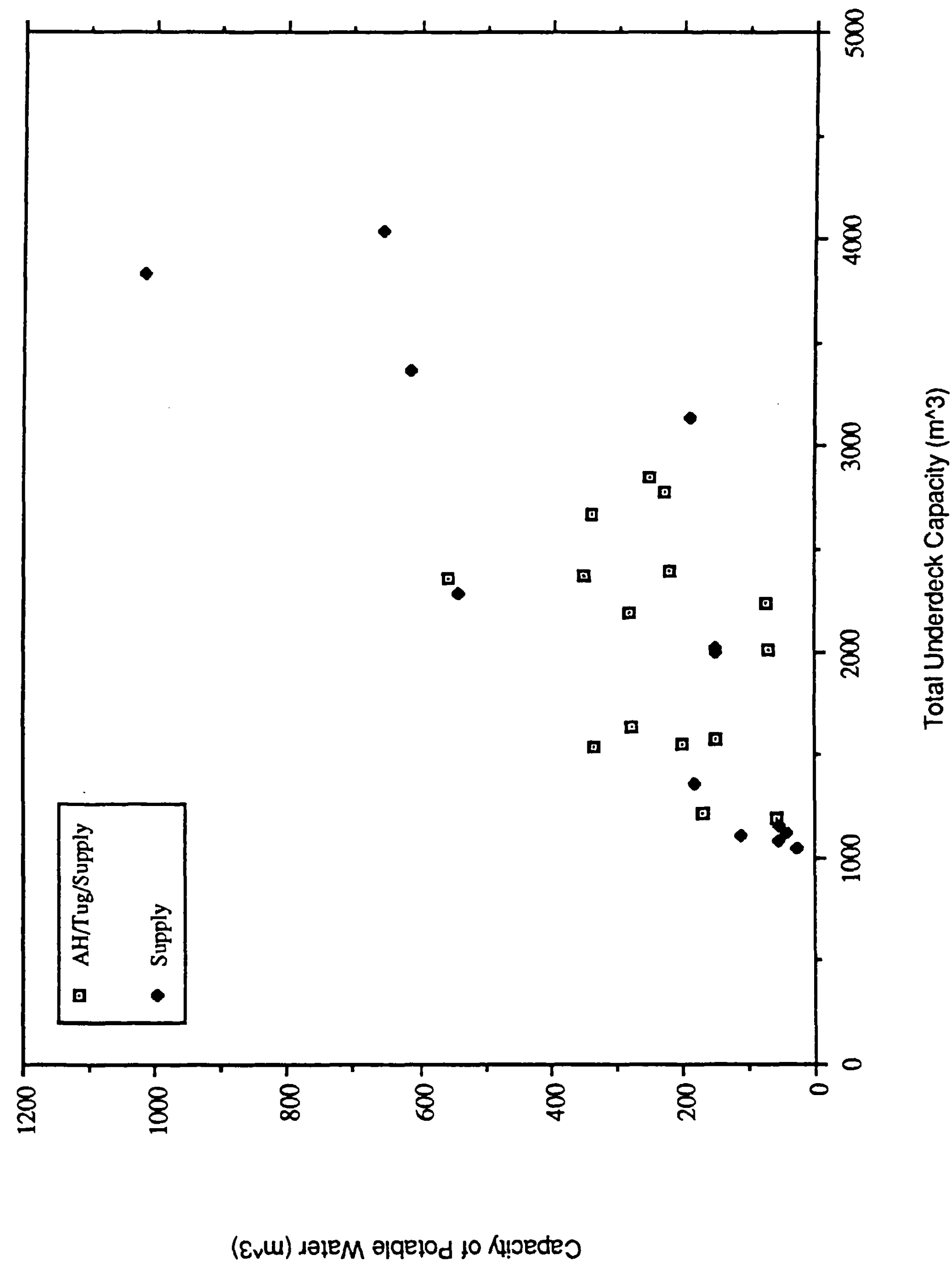

Fig. 3.6 Relation Between Capacity of Potable Water and Total Underdeck Capacity

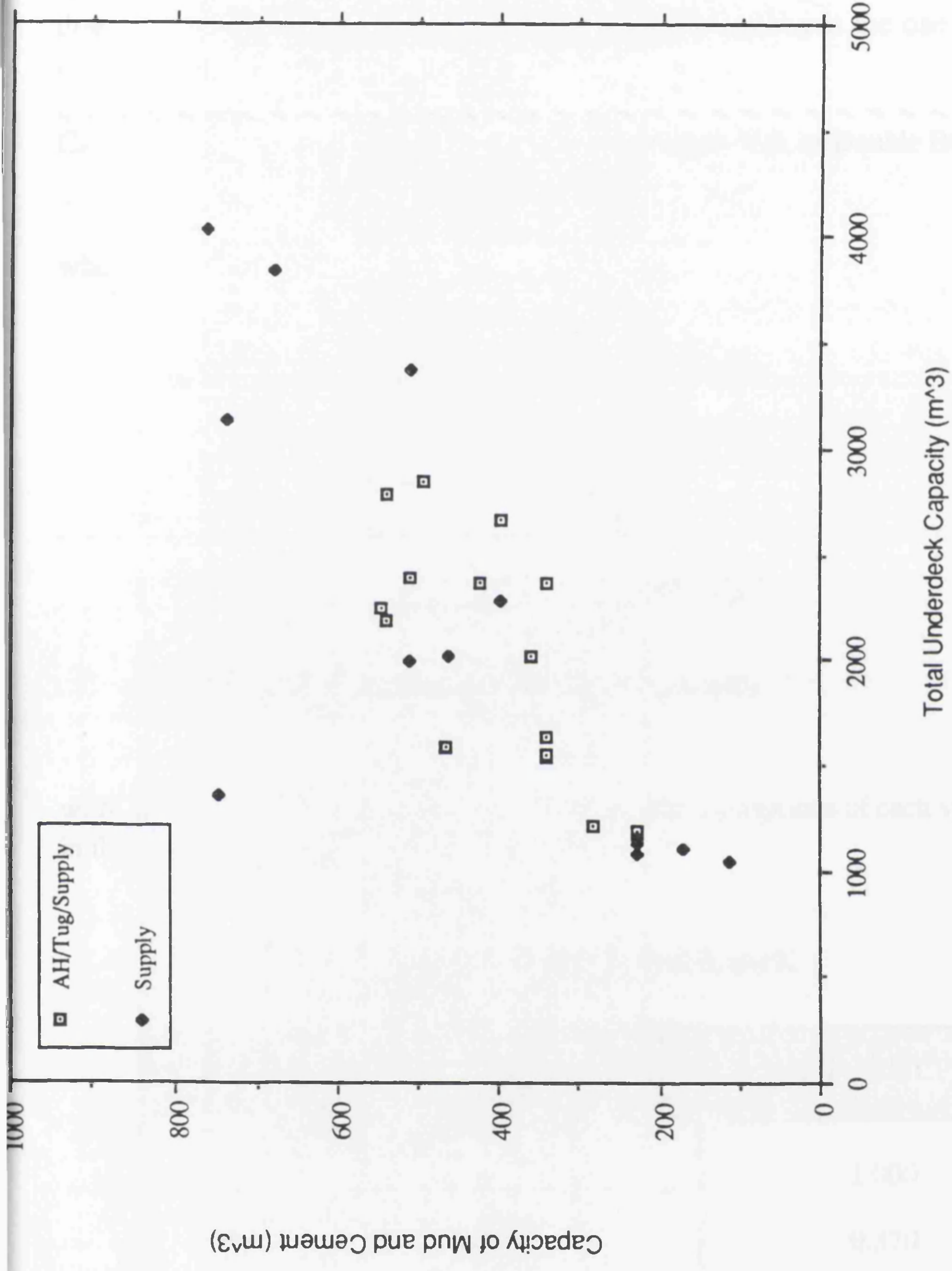

Fig. 3.7 Relation Between Capacity of (Mud and Cement) and Total Underdeck Capacity

3.5.3 Method of Estimating Underdeck Capacity

The estimation of under deck capacity normally requires the knowledge of the hull form, which can either be derived from offsets or assuming a standard hull form. In this study, the method used to evaluate the cargo capacity is the one developed by *Lamb* [14] in 1969 where

Cargo Capacity = (Total Vol. of Hull - Vol. of Peaks - Vol. of Double Bottom Tanks - Vol. of Machinery Space)

Eqn. 3.18

where

$$\text{Total Vol. of Hull} = LB\left[D + \frac{S_f + S_a}{6} + \frac{2C_r}{3}\right]C_B K_1 \qquad \text{Eqn. 3.19}$$

$$\text{Vol. of Peaks} = L_p B\left[D + \frac{S_f + S_a}{2}\right]C_B K_2 \qquad \text{Eqn. 3.20}$$

$$\text{Vol. of Double Bottom Tanks} = (L - L_p)BD_{tt}C_B K_3 \qquad \text{Eqn. 3.21}$$

$$\text{Vol. of Machinery Space} = L_{er}B(D_{er} - D_{tt})C_B K_4 \qquad \text{Eqn. 3.22}$$

with values of coefficient given in Table 3.4 while descriptions of each symbol is given in the main nomenclature.

Table 3.4 Values of Coefficient K

ITEM	PURE SUPPLY	AH/TUG/SUPPLY
K_1	1.050	1.000
K_2	0.370	0.370
K_3	0.975	1.170
K_4	0.800	0.850

Table 3.5 shows the capacity of various offshore supply vessel and those calculated from the above method.

3.6 CONCLUSION

As in all types of vessel, a good estimation of mass and capacity is vital for the preliminary design of offshore supply vessels. This chapter has put forward various equations to determine the mass and capacity of present offshore supply vessels. It was found that equations used in the design of such vessels in the fifties are obsolete and therefore not suitable to be used in present day preliminary design of such vessels.

Table 3.5 Comparison Between Calculated and Actual Capacity

VESSEL	TYPE	ACTUAL CAPACITY (m^3)	CALCULATED CAPACITY (m^3)	% DIFFERENCE
Seaforth Emperor	Supply	4389.00	4331.00	- 1.3
Seaforth Sovereign	Supply	2766.00	2722.00	- 1.6
Stad Neptune	Supply	4495.00	4449.00	- 1.0
Stirling Elf	Supply	1783.50	1687.00	- 5.4
TNT Tiger	Supply	1741.45	1720.00	- 1.2
Pacific Shogun	AH/Tug/Supply	1346.70	1471.90	+ 9.3
Pagentrum	AH/Tug/Supply	2468.10	2576.00	+ 4.4
Seaforth Centurion	AH/Tug/Supply	2833.30	3052.00	+ 7.7
Seaforth Conqueror	AH/Tug/Supply	2598.00	2677.00	+ 3.0
Maersk Handler	AH/Tug/Supply	2187.60	2197.00	+ 0.4

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CHAPTER 4

POWERING AND PROPULSION

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POWERING AND PROPULSION

4.0 INTRODUCTION

A matter central to the design of offshore supply vessels is the powering. From Fig. 4.1, it is clear that offshore supply vessels have more installed power than ordinary cargo vessels of the same deadmass. Economically, putting power into a vessel is one of the most expensive items at the building stage. Powering is important since installed power affects capital cost and using power affects running cost.

Powering requirements for pure supply vessels are rather different from that for anchor handling/tug/supply vessels. The former may have more power than expected by comparison with ordinary cargo vessels but it may not always be used as when time is unimportant, a return to port may be made with one engine and one propeller alone. If time is important, then full power is utilised and an excess of power while only adding marginally to speed may be seen as an advantage by a charterer and gain the charter.

Anchor handling/tug/supply vessels usually have power dictated by bollard pull or tow rope pull at a certain speed. This usually means that they can be overdriven when in the supply vessel mode but this may be an advantage to gain work. As an example in the case of vessels of the same size namely 54.86 m long, 12.19 m beam and 4.27 m depth. One was fitted for use as a supply vessel with 1680 kW giving a speed of 12 knots while another was fitted with 2390 kW for a bollard pull of 30.8 tonnes but giving a free speed of 13 knots.

For supply vessels with a target speed then the propeller and machinery can be optimised for it although consideration will also be given to efficient running at lower speed. As for anchor handling/tug/supply vessels, the propeller and machinery may be optimised for towing at a modest speed or indeed for bollard pull and the resulting possibly excessive free running speed at full power accepted provided efficient running at lesser power is possible.

In this study, the estimation of the powering and propulsion requirements will be based on two separate modules. The first module will be suitable for the pure supply vessels while the second module will be used for the anchor handling/tug/supply vessels and based on bollard pull.

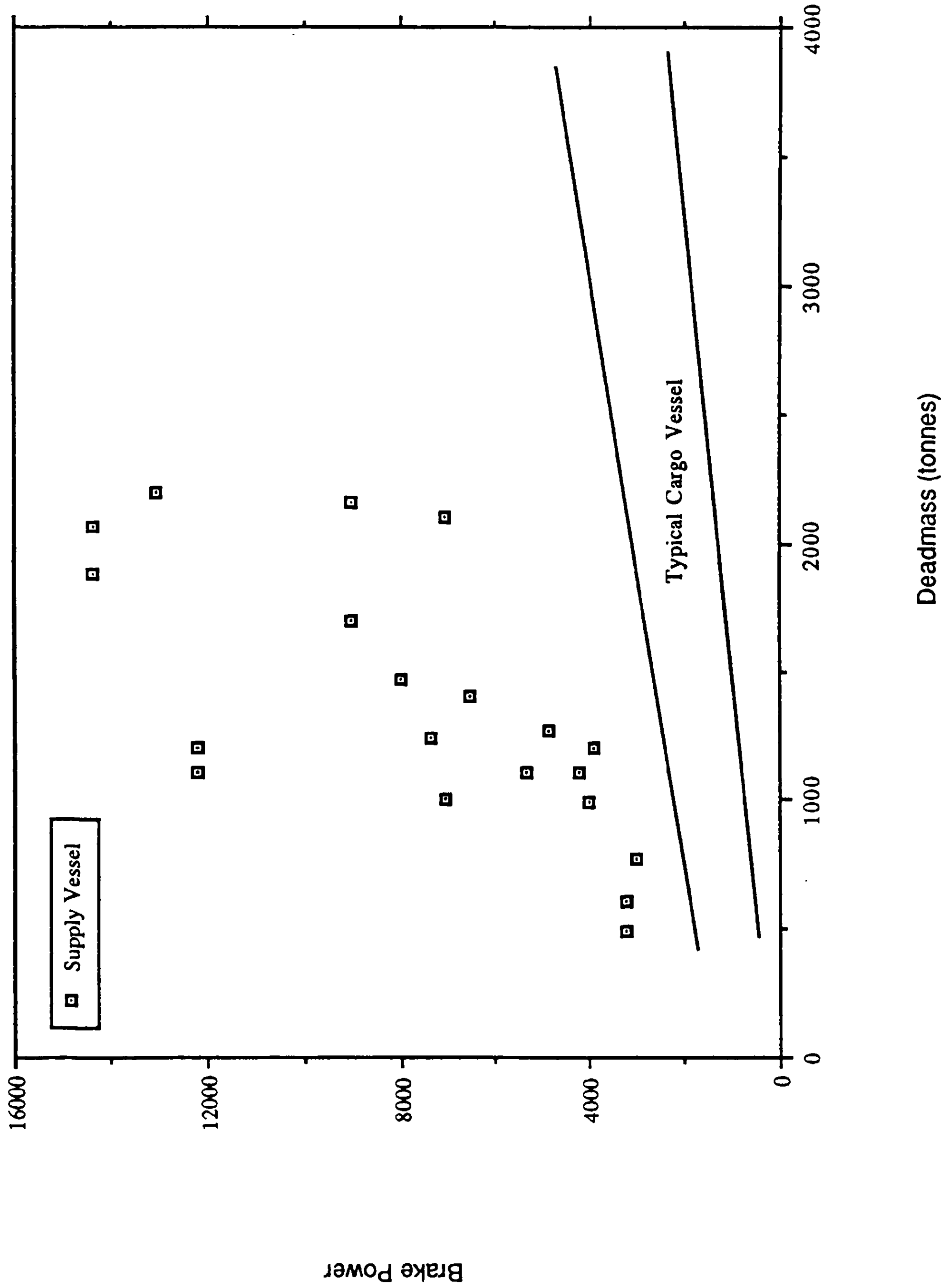

Fig. 4.1 Comparison Between Supply Vessels and Cargo Vessels on the Basis of Power

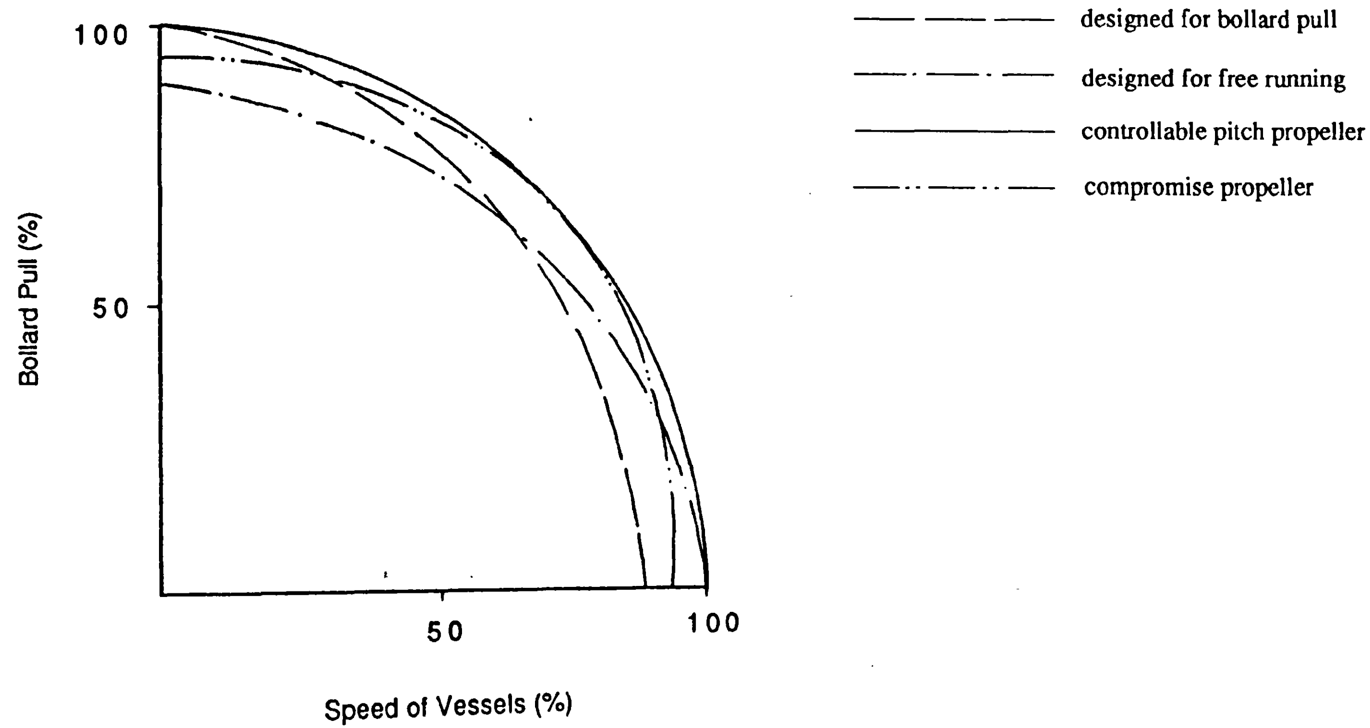

Fig. 4.2 Compromise Between Bollard Pull and Speed [7]

4.1 STANDARD METHOD OF ESTIMATING POWER

Although model towing tank tests will be carried out before a design is finalised, at the preliminary design stage methodical series prediction are needed corrected by the results of past ships series predictions compared to their trial results.

Offshore supply vessels are at or beyond fringe values of standard series with the displacement length ratios of 30.0 and length/beam ratios below 5.0 and *Froude* Number from 0.24 to 0.34.

In this study, a statistical method developed by *Holtrop* and *Mennen* [12], [15] for the determination of required propulsive power is adapted. This method was developed through a regression analysis of random model experiments and full-scale data available at the *Netherlands Ship Model Basin.*

4.2 EFFECTIVE POWER PREDICTION

The total resistance of the offshore supply vessel is subdivided into various components such as :

$$R_T = R_F(1+k) + R_{APP} + R_W + R_{TR} + R_A \quad \text{Eqn. 4.1}$$

where

R_F = frictional resistance according to the *ITTC 1957* friction formula

$1 + k$ = form factor describing the viscous resistance of the hull form in relation to frictional resistance

R_{APP} = resistance of appendages

R_W = wave-making and wave-breaking resistance

R_{TR} = additional resistance of immersed transom stern

R_A = model-ship correlation resistance

The added pressure resistance of a bulbous bow near the water surface is neglected as most offshore supply vessels do not have such projections. The regression formulae for each component of resistance were also provided by *Holtrop.*

Once the total resistance is known, the effective power of the offshore supply vessel can be calculated from

$$P_E = (R_T \times V) \times k_2 \text{ in kW} \qquad \text{Eqn. 4.2}$$

where k_2 is the factor incorporating wind resistance.

4.3 PREDICTION OF DELIVERED POWER

Once the effective power of the vessel is known, the power delivered to the propeller can be predicted by estimating the value of the quasi-propulsive coefficient. The quality of the propulsive performance is determined by that of quasi-propulsive coefficient. Simple relationships have been suggested for the prediction of this coefficient by Emerson [18] updated by *Watson* and *Gilfillan* [17], and *Moor* [19]. However, these relationships are for single screw ships. With twin screw the quasi-propulsive coefficient (QPC) is generally close to the open water propeller efficiency and consequently it is useful to determine the components of the QPC separately.

4.3.1 Propeller Design

While today, many advanced propellers are designed against a theoretical background, a suitable standard for assessment is the *Wageningen-Troost* B-Series results at the NSMB [23]. In this study, the propeller design is based on the 'Optimum Efficiency Equations of the NSMB Propeller Series' [16], in which the *Wageningen* B-Series propeller information was expressed by equations. For predetermined values of blade area ratio and B_p,the optimum efficiency equation is

$$\delta, P/D, \eta_{opt} = A_0 + A_1(\ln B_p) + A_2(\ln B_p)^2 + A_3(\ln B_p)^3 + A_4(BAR) + A_5(BAR)^2 + A_6(BAR)^3 + A_7(\ln B_p)(BAR) + A_8(\ln B_p)(BAR)^2 + A_9(\ln B_p)^2(BAR)$$

Eqn. 4.3

where A_0, A_1, ...A_9 are the regression coefficients given by Sabit [16] and BAR is blade area ratio of propeller.

(a) *Selecting Propeller RPM*

To obtain an efficient propeller, its RPM should be reasonably low. Typical values for offshore supply vessels are in the range of 190 to 250 revolutions per minute corresponding to engine RPM of between 750 to 1200 and reduction gearing.

(b) *Selecting Propeller 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. This may limit the propeller diameter to about 65% of the design draft.

(c) *Selecting Blade Area Ratio*

Cavitation consideration governs the selection of appropriate value of the blade area ratio (BAR) of the propeller. For maximum propeller efficiency, the BAR must be as small as possible and cavitation considerations require that the BAR must be above a minimum value. Thus, the program incorporates the smallest value of BAR which also satisfies the cavitation criterion. The cavitation criterion was given by *Burill* [24] as the permissible upper limit of back cavitation. And the line representing 7.5% of back cavitation was thought to be acceptable. Modern highly skewed blades also restrict cavitation.

The statistical prediction formulae for estimating the Taylor's wake fraction, thrust deduction factor and relative rotative efficiency are given as follows:

$$w_T = 0.3095C_B + 10C_VC_B - 0.23D\sqrt{BT} \qquad \text{Eqn. 4.4}$$

$$t = 0.325C_B - 0.1885D\sqrt{BT} \qquad \text{Eqn. 4.5}$$

$$\eta_R = 0.9737 + 0.111(C_P - 0.0255lcb) - 0.06325P/D \qquad \text{Eqn. 4.6}$$

where

lcb = longitudinal position of the centre of the buoyancy forward of 0.5L as a percentage of L

P = propeller pitch

C_V = viscous resistance coefficient

4.4 SERVICE MARGIN

Service margin serves as an allowance for the differences in the power requirements of a vessel between its trial condition and its 'average' service condition. The standard practice is by adopting a power margin, such that the design speed is reached on trials at 80% of the normal power giving a power margin of 25%. In this study, the service margin is assumed to vary linearly from 15% at a *Froude* number of 0.24 to 25% at a *Froude* number of 0.35 and above [25].

4.5 DESIGN FOR BOLLARD PULL

One of the reasons for the existence of the anchor handling/tug/supply vessel is the pulling of drilling rigs or barges. Such vessels operate under various conditions, that is, free running, towing at some intermediate speed and bollard pull. Bollard pull is defined as the maximum pull the vessel can apply at zero speed or the amount of power available to control a tow. The resistance of these vessels themselves, while towing, is only a small percentage of the overall tow rope pull exerted.

Many approximations have been stated for the relationship between delivered powers and bollard pull. They include *Argyriadis* [6] who quoted that for vessel *L.E. Norgaard*, the expected pull is about 15.2 kg/kW while for the vessel *D.S. Simpson*, 18 kg/kW. Figure 4.3 shows the relationship for twenty anchor handling/tug/ supply vessels built since 1980.

$$\text{Power (kW)} = -454.94 + 64.466\ \text{(BOLP)} \qquad \text{Eqn. 4.7}$$

where BOLP = bollard pull in tonnes.

The design of a propeller for bollard pull introduces four issues;

a. choice of the propeller's main dimensions,
b. estimation of the bollard pull,
c. estimation of the vessel's free running speed,
d. estimation of the vessel's overall towing performance.

The vessel's free running speed and towing performance depend on the choice of the optimum propeller for the required bollard pull and can be estimated from the hull resistance and the machinery characteristics such as power and rpm. The choice of the propeller dimensions for bollard pull revolves around one main criterion, that is, to install the largest diameter propeller possible with considerations of the vessel's draught and the hull-propeller clearance. The maximum practical diameter of an open propeller is about 65 percent of the draught aft. According to Isin [6], the rpm of the propeller should be chosen, if possible, to keep the pitch-diameter ratio (P/D) between 0.6 and 1.25 with the best bollard pull resulting from P/D of about 0.6. The maximum blade area ratio should be between 0.50 and 0.55 in order to give all round towing performance and high astern bollard pull.

During bollard pull condition when the vessel speed is zero, the propeller advance coefficient (J) is given by:

$$J = \frac{V_A}{ND} \qquad \text{Eqn. 4.8}$$

where

V_A = propeller advance speed
N = propeller revolutions per unit time
D = propeller diameter

For preliminary design purposes, Argyriadis [20] gives the following equations for the bollard pull and the corresponding rpm N :

$$T(kg) = 716 x \frac{BHP_o \, x \, T_c}{N_o \, x \, D} \qquad \text{Eqn. 4.9}$$

with

$$T_c = \frac{60}{2\pi D} \, x \, \frac{K_T}{K_Q} \qquad \text{Eqn. 4.10}$$

$$N = 60 \, x \left(6.55 \, x \, \frac{BHP_o}{N_o \, x \, D^5 \, x \, T_r} \right)^{1/2} \qquad \text{Eqn. 4.11}$$

with $T_r = K_Q$.

BHP_o = brake power at design speed
N_o = propeller rotational speed (rpm) at design speed.

The values of T_c and T_r are given in Fig. 4.4. as a function of the propeller pitch-diameter ratio for three and four bladed propellers with a disk-area of 0.50.

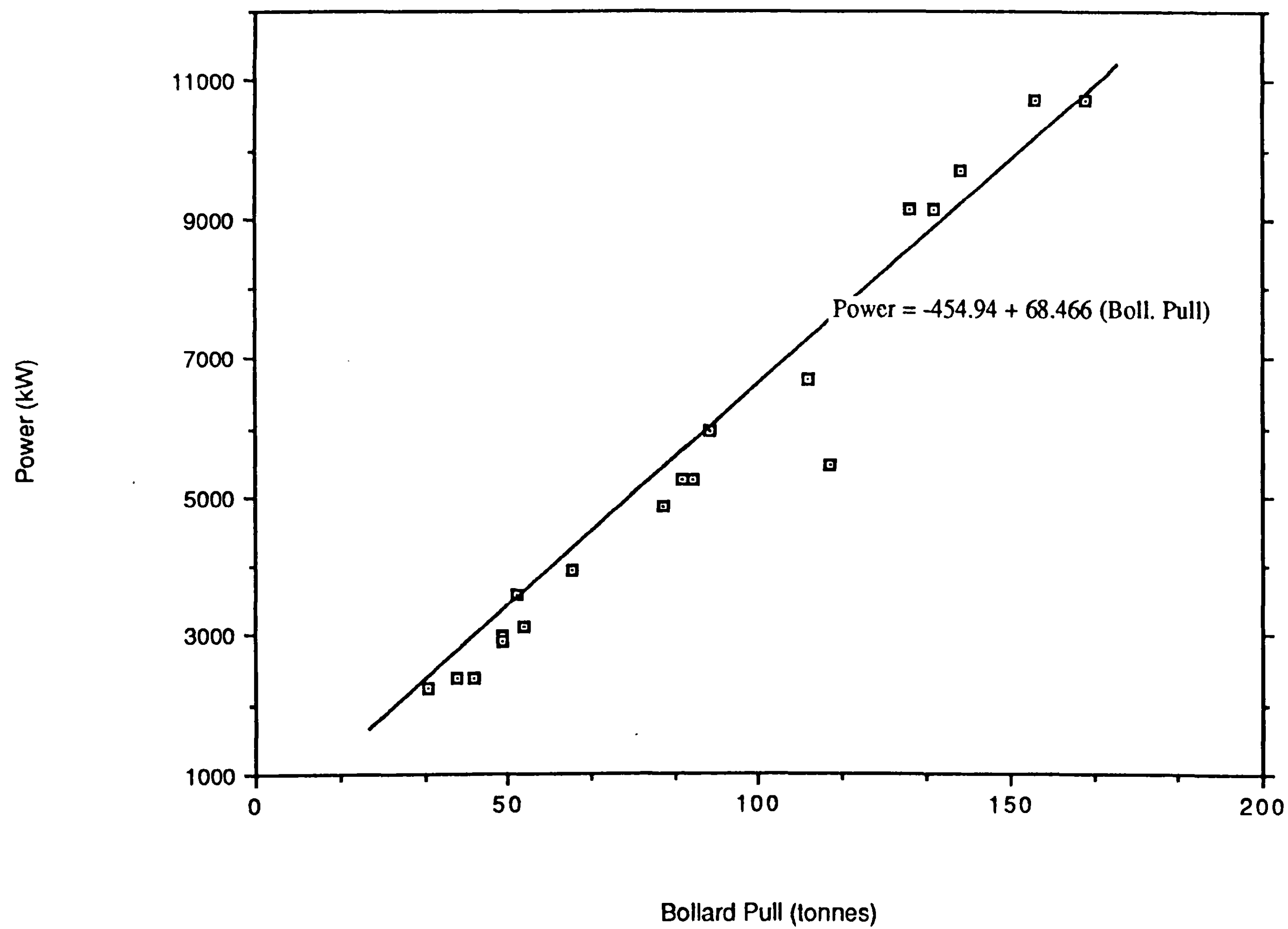

Fig. 4.3 Relation Between Bollard Pull and Power

In the discussion to reference [20], both Kimon and Morgan point out that the coefficient from Fig. 4.4 can be strictly applied only to constant-torque installations. Morgan [1] derived the expression for the bollard pull and the corresponding rpm for constant-power installations for three, four and five-bladed Troost B- Series propellers with different expanded area ratios. Figure 4.5 reproduced here are for the four bladed propeller data.

The corresponding equations (in metric system) for constant torque are :

$$T(kg) = 716 x \frac{P_D x T_c}{N_o x D} \qquad \text{Eqn. 4.12}$$

with $T_c = K_T/K_Q$

$$N = 60 x \left(6.85 x \frac{P_D}{N_o x D^5 x T_r} \right)^{1/2} \qquad \text{Eqn. 4.13}$$

with $T_r = K_Q$.

At bollard pull, the relationship between thrust, propeller diameter, and engine delivered power can be easily derived by eliminating the revolutions per seconds from the definition of the thrust coefficient, the torque coefficient, and the engine delivered power. Thus by definition

$$K_T = \frac{T}{\rho n^2 D^4}, \quad K_Q = \frac{Q}{\rho n^2 D^5}, \quad \text{and} \quad P_D = \frac{2\pi n Q}{75}$$

then

$$T = C_T x (P_D x D)^{2/3} \qquad \text{Eqn. 4.16}$$

where

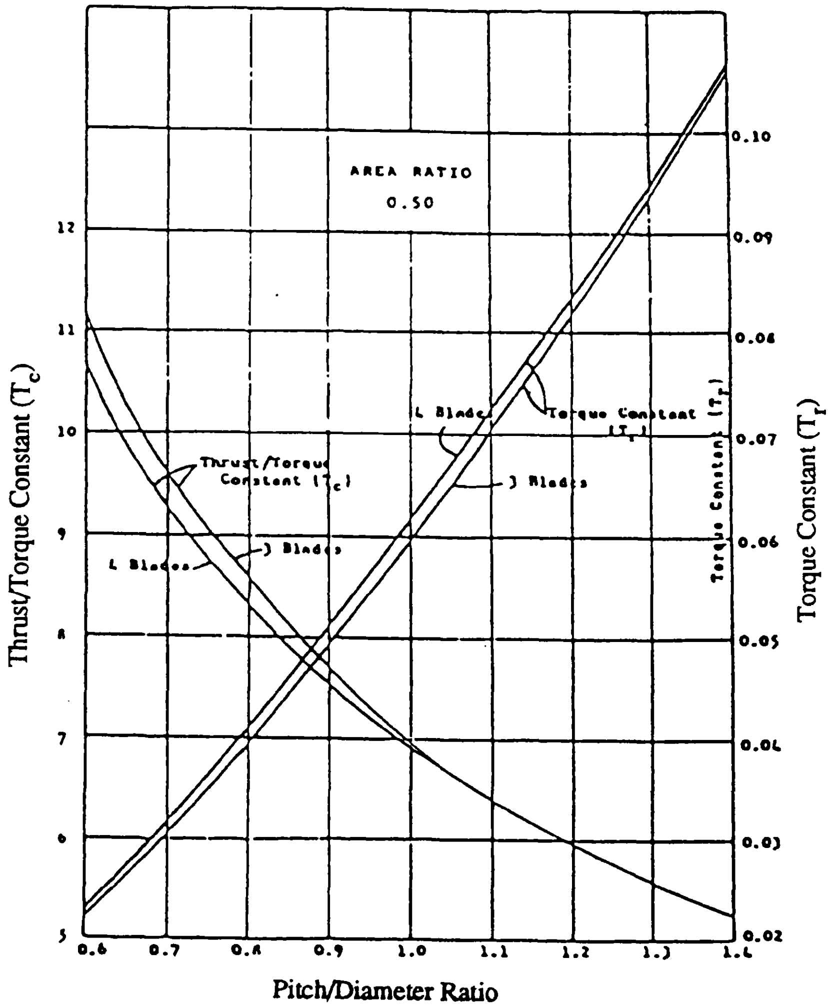

Fig. 4.4 Pitch/Diameter Ratio Against T_c and T_r [6]

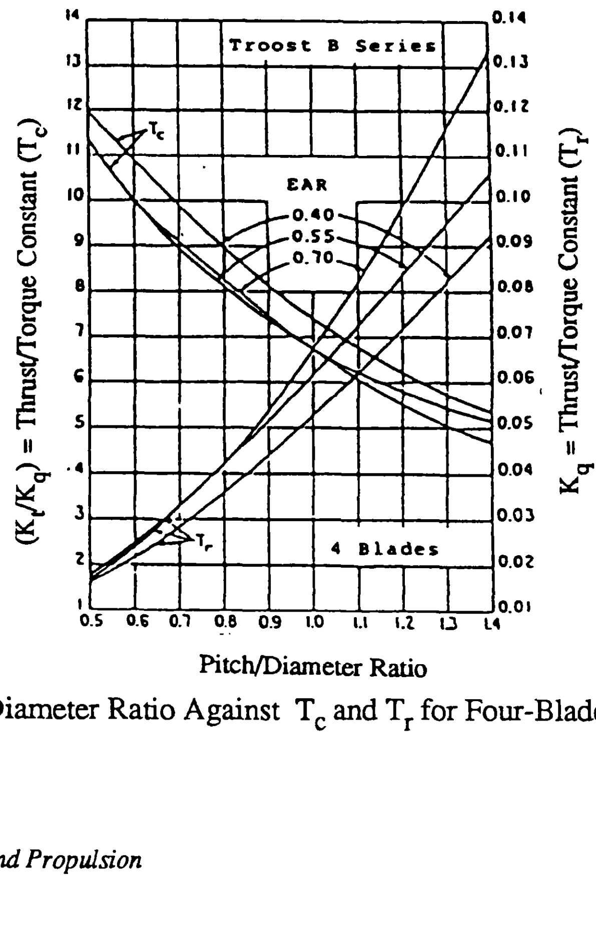

Fig. 4.5 Pitch/Diameter Ratio Against T_c and T_r for Four-Bladed Propellers [6]

$$C_T = \left(\frac{75}{2\pi}\rho^{1/2}\right)^{2/3} x \frac{K_T}{K_Q^{2/3}} \qquad \text{Eqn. 4.17}$$

The revolution per second can be obtained by eliminating the propeller diameter from the expression for K_T, K_Q and T. Thus

$$n = C_N \, x \frac{P_D^2}{T^{5/2}} \qquad \text{Eqn. 4.18}$$

where

$$C_N = \frac{75}{2\pi} C_T^{2/3} \, x \frac{K_T}{K_Q^{2/3}} \qquad \text{Eqn. 4.19}$$

At bollard pull, where J = 0, the values of C_T and C_N are functions of the coefficients K_T and K_Q and they can be computed from any chosen propeller series charts for different values of pitch-diameter ratio and of expanded area ratio (EAR).

The value of EAR to avoid cavitation thrust break down and erosion has been derived by Caldwell [22] from an analysis of Burrill's cavitation chart assuming approximately 2.5% back cavitation. This formula is given by

$$EAR_o = C x \frac{\left(P_D / A_p\right)^{2/3}}{V_{tip}^{0.72}}$$

$$= \left[\frac{4 x C^{3/2} x P_D}{\pi x D^2 p x (\pi n D)^{1.08}}\right]^{2.05} \qquad \text{Eqn. 4.20}$$

where

p = propeller projected area - expanded area ratio
= A_p/A_E = 1.067 - 0.229 P/D

By substituting the expressions for n and D for the Wageningen B-Screw Series, EAR_o can be written as

$$EAR_o = C_{EAR} \times \left(\frac{P_D}{T}\right)^{0.768} \qquad \text{Eqn. 4.21}$$

where

$$C_{EAR} = 0.67 \frac{C^{0.6}}{p^{0.4}} \times \left(\frac{C_T^{01.848}}{C_N^{0.432}}\right) \qquad \text{Eqn. 4.22}$$

Curves of C_T, C_N and C_{EAR}, developed from the appropriate charts, can be plotted as functions of P/D and EAR and used to give a quick estimation of the propeller dimensions for a given power and required bollard pull. Such curves are given in Figs. 4.7, 4.8 and 4.9 [6].

4.6 CONCLUSION

This chapter presents methods of evaluating the powering of the offshore supply vessels. An accurate estimate of the power required is an important part of preliminary ship design. This is likely to be checked by model tests as design is finalised. The complete computer algorithm for powering and propulsion are shown in Figs. 4.10 and 4.11. To validate the power given by this study, actual values during trials for two vessels are compared as shown in Fig. 4.12 to Fig. 4.13. As can be seen from these plots, the output given by this study are in close agreement with those from existing vessels.

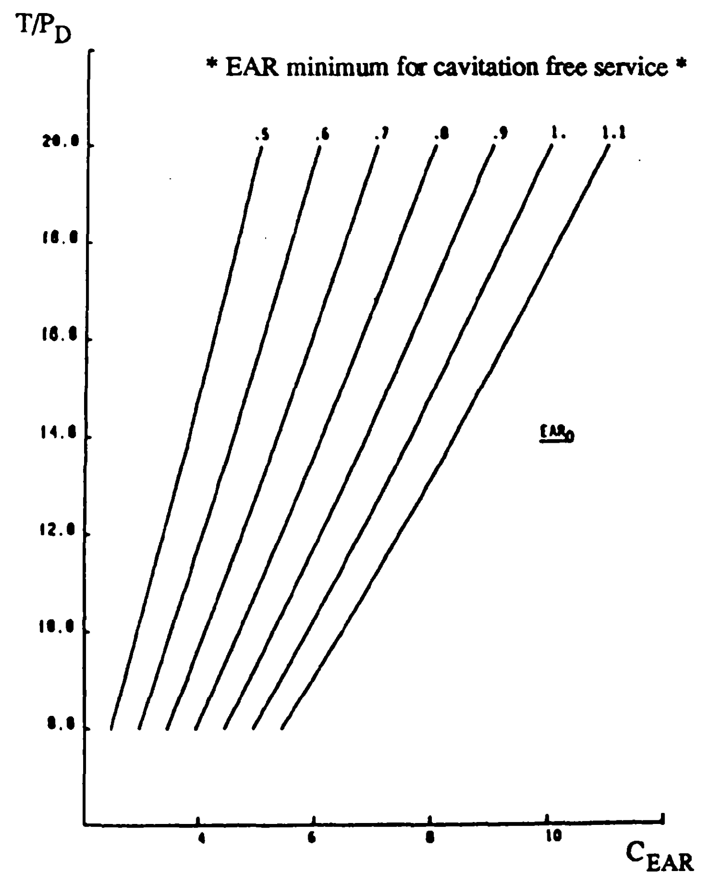

Fig. 4.6 Diagram of Minimum EAR for Cavitation Free Service

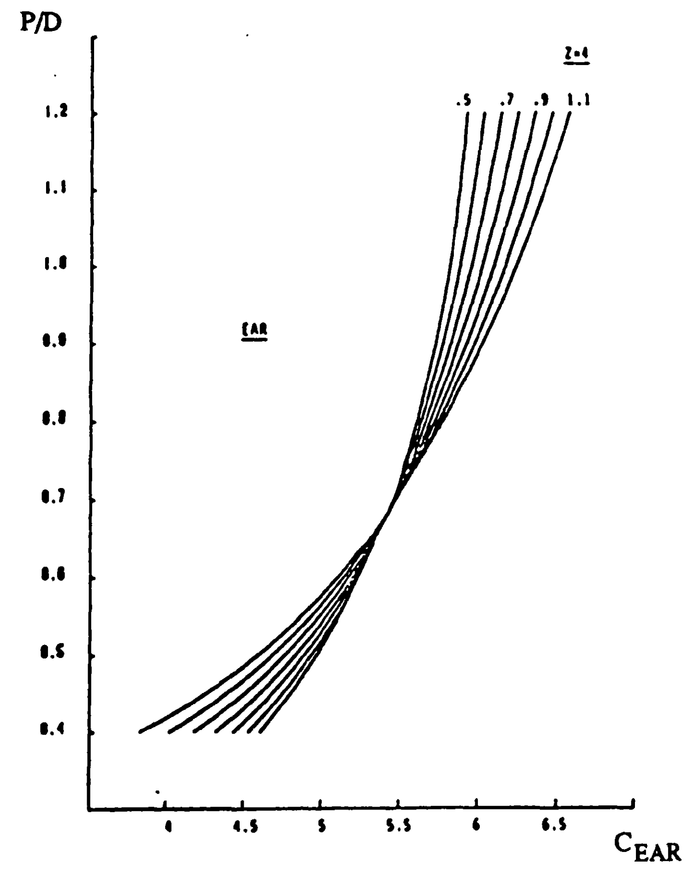

Fig. 4.7 C_{EAR} Against P/D for Four-Bladed Propellers

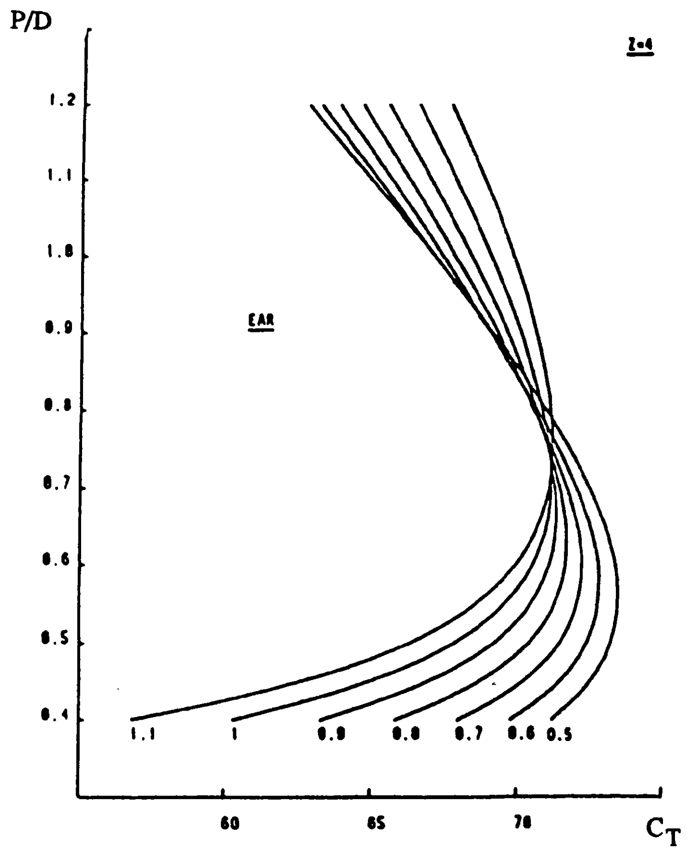

Fig. 4.8 C_T Against P/D for Four-Bladed Propellers

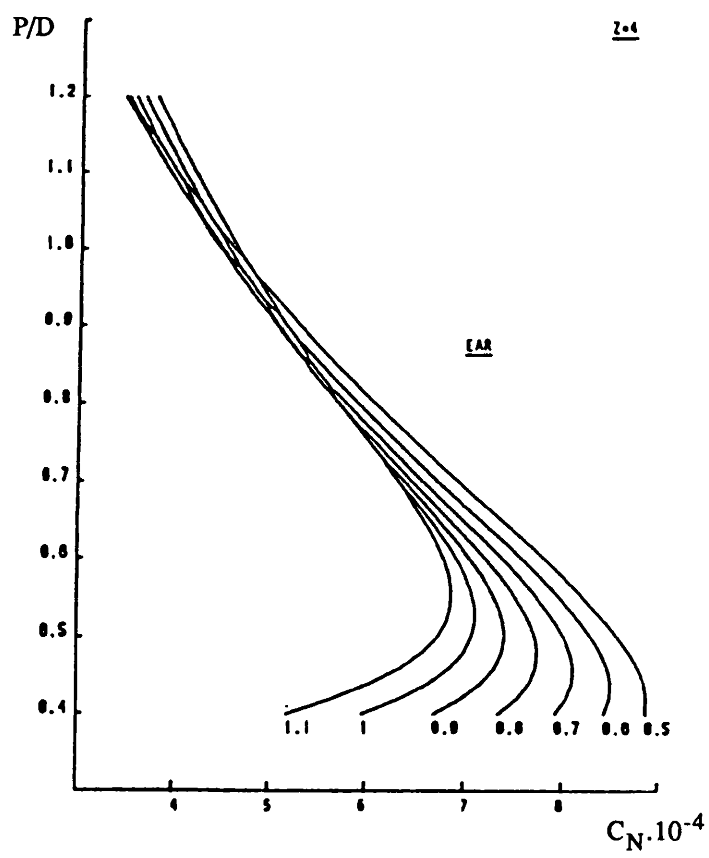

Fig. 4.9 C_N Against P/D for Four-Bladed Propellers

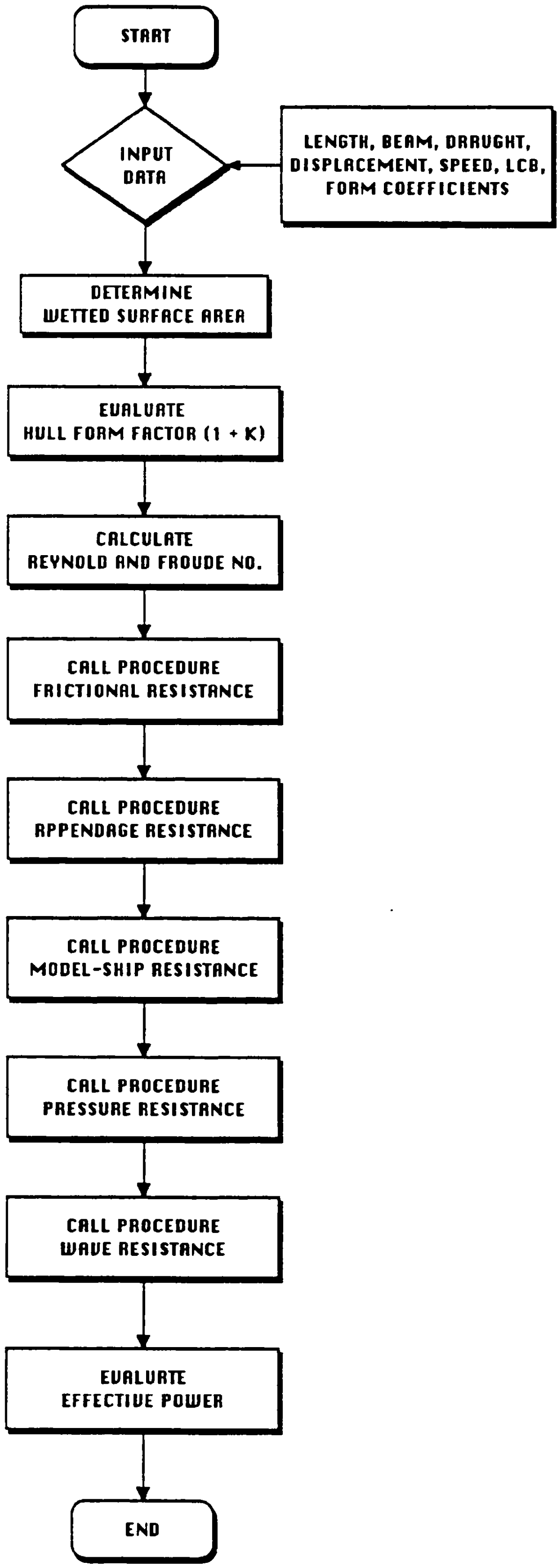

Fig. 4.10 Flowchart for the Effective Power Algorithm

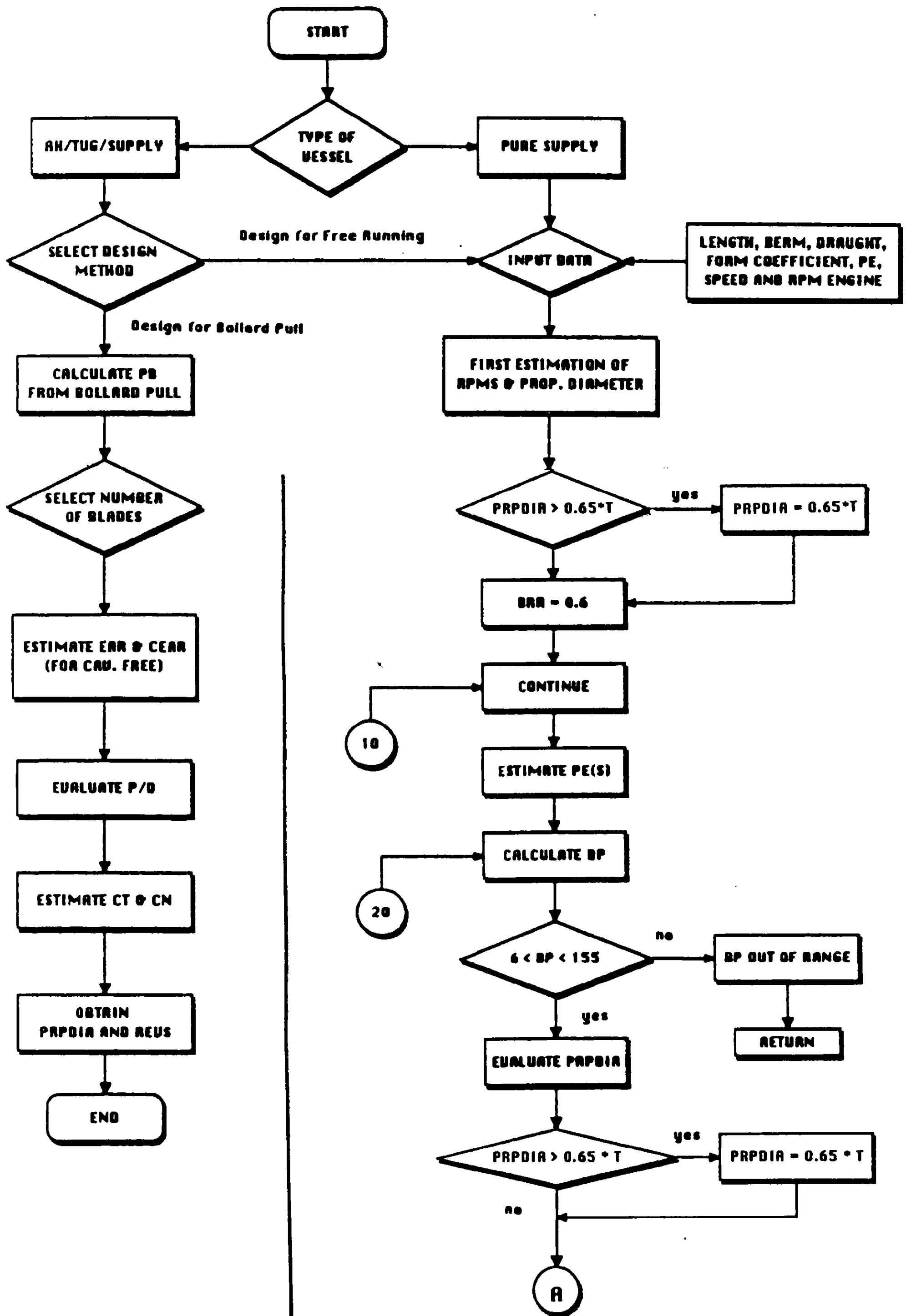

Fig. 4.11 Flowchart for the P_B and Propulsion Algorithm

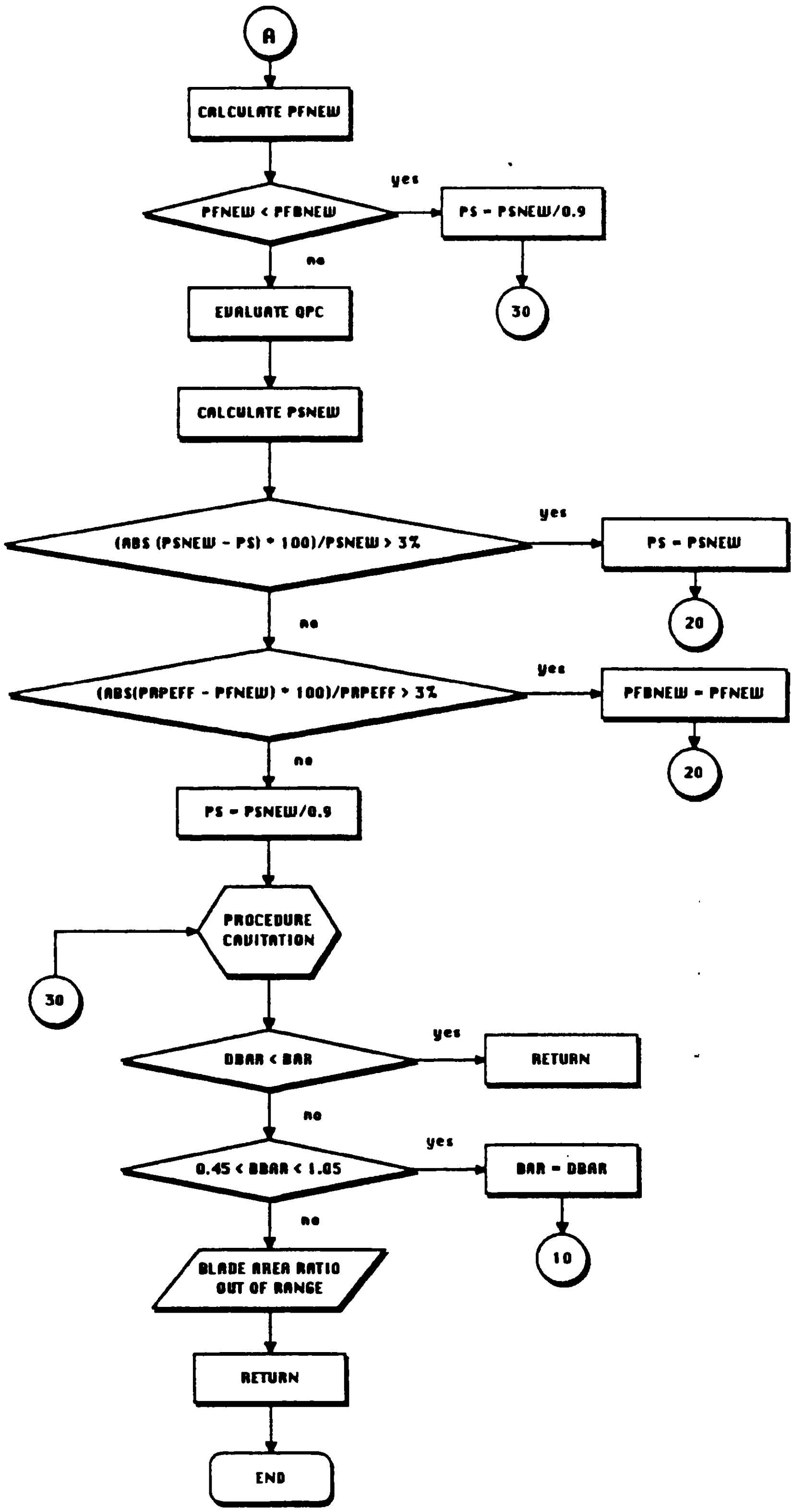

Fig. 4.11 Flowchart for the P_B and Propulsion Algorithm (continue)

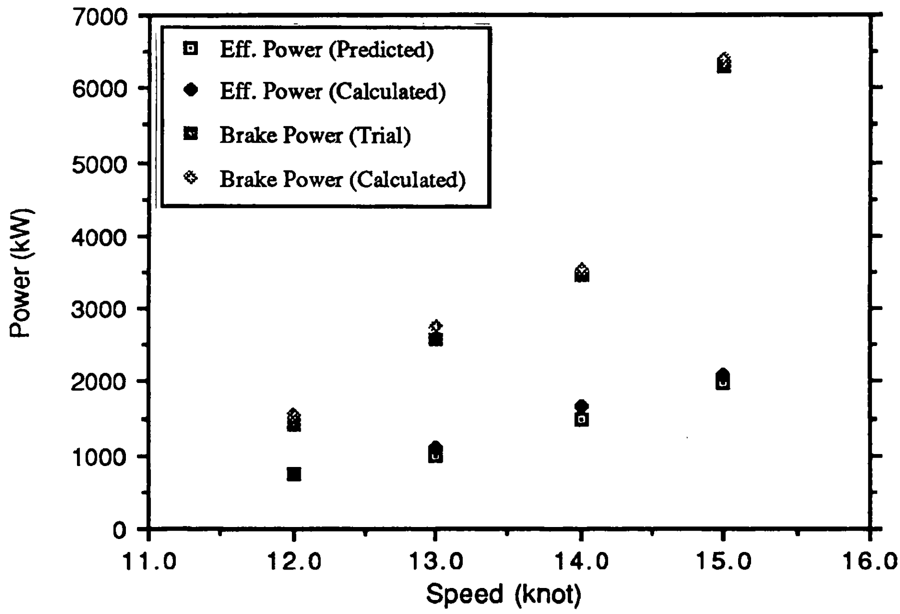

Fig. 4.12 Comparison Between Predicted P_E and Trial P_B with Calculated Values (Vessel 1)

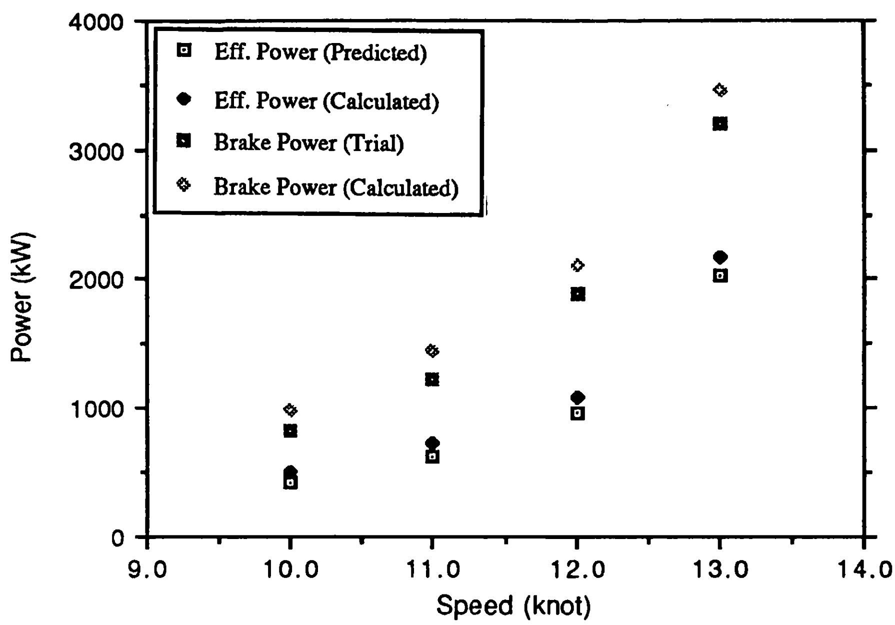

Fig. 4.13 Comparison Between Predicted P_E and Trial P_B with Calculated Values (Vessel 2)

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CHAPTER 5

SEAKEEPING CHARACTERISTICS

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5.0 INTRODUCTION

Offshore supply vessels are generally required to remain operational in severe sea conditions where crew comfort is perhaps less important than the ability of the vessel to continue its task. Thus ship motions and accelerations tend to be accepted providing they are not so large that the ship has to cease operations, either for safety reasons or because of the inability of the crew to continue work. As regards to wetness, North Sea vessels in particular usually incorporate high freeboard at the bow and a substantial bulwark all round to ensure that green water taken on board is kept to an acceptable level to minimise structural damage and hazard to the crew.

Seakeeping is the general term used to describe the safety, effectiveness and comfort of a ship in waves. It is mainly concerned with the motions out of the horizontal plane, that is with heave, pitch and roll. The prediction and minimisation of such motions is of great importance in ship design since large amplitudes of these motions have a number of deleterious effects. These include discomfort and loss efficiency of the crew, seasickness and possible injury to human and damage to equipment from the high accelerations that can be produced. Extreme rolling can also lead to flooding, shifting of cargo and even capsize. Other direct effects on the ship include loss of ship speed, deck wetness and slamming.

Deck wetness occurs when bow immersion allows spray or green seas to cover the upper deck forward. Slamming can lead to severe impulsive loading on the hull as the hull re-enters the water at a high relative velocity such that the bottom plating impacts violently on the water surface. This phenomena is usually known as bottom slamming. It can cause overall vibration of the hull and local damage to the plating.

In short, for commercial ocean going vessels such as of the offshore supply vessels, seakeeping performance is principally addressed in terms of three main aspects, that is, habitability, operability and survivability.

Habitability is concerned with providing the crew with an environment that permits them to function effectively without degrading their performance because of the interaction of the ship with the sea. The complex missions which ships are assigned for today require an alert work force, capable of making good judgements and performing delicate and, at the same time, physically demanding work.

Operability is concerned with the ability of the crew to operate the ship with all its mechanical equipment so as to carry out the assigned mission in the ocean environment in which the ship is expected to encounter. This includes such things as keeping instrument operating, ensuring the safety of the deck equipment, holding course in quartering seas, and all the necessary work that must be done.

Survivability is concerned with what happens to the ship when condition become so rough that the ship or any of its major subsystems are in danger of damage or destruction. The environment now becomes one of those very severe storms that is experienced by a ship only once or twice in its lifetime. Habitability is no longer a factor of primary concern, and operability is important only with respect to the most essential systems.

In practice, the boundaries between habitability and operability aspects of seakeeping performance are vague and the two will always be considered together. The third aspect is usually not considered in detail by the designer and is generally assumed to be satisfied by adherence to appropriate classification rules, load line and stability regulations.

By describing seakeeping performance in terms of physical parameters such as absolute and relative motions, accelerations, deck wetness and slamming, it is possible to quantify performance and subsequently evaluate performance in a rational and systematic manner. Limiting values for individual performance criteria have been derived from full scale and operational experience. These are :

a. Design limits - Absolute limiting values which are not to be exceeded in service.

b. Operational limits - Limiting values beyond which performance degradation or increasing likelihood of vessel or cargo damage will occur.

Model experiments are a reliable method to predict the various aspects of ship performance before the actual ship is built. However, in view of the cost and time involved, the amount of model testing in the early stages of design is usually restricted, unless important innovations are involved in the design. In the preliminary design phase, use is made of empirical rules based on the results of previous model tests for estimation of the hydrodynamic performance. But because of the large number of parameters involved, and the complexity of their relationship, no empirical methods based on measured data have been developed for seakeeping performance in the past. Fortunately, there is a very successful theoretical prediction method available, which is basically a linear two-dimensional theory, which assumes the ship hull to be slender and the forward speed low. The theory gives remarkably good results for ship motions even with the length over beam ratio as low as 4.0 and values of the *Froude Number* as high as 1.0, as was demonstrated by *Blok* and *Beukelman* [10].

Due to the limited computational effort needed for strip theory calculations, this method is very useful for the preliminary design stages of a vessel.

5.1 CONCEPT OF FLUID FORCES ON A CYLINDER IN WAVES

The basic understanding of ship motion can easily be studied by considering the case of a freely floating cylinder in a train of regular harmonic (sinusoidal) waves which are long with respect to the cylinder.

When surface waves pass through a floating body, the ambient fluid will exert hydrodynamic forces and moments on the body. These forces and moments consist of two components, that is, the unsteady exciting components, which are known as the first order forces, lead to the body oscillations and these components are linearly proportional to the wave height. On the other hand, the second order forces are attributed to the non-linear effects and these components are generally small and proportional to the square of wave height.

The first order oscillatory forces can be divided into two main components, namely the viscous force and the pressure force. The viscous force, F_V is brought about by the fluid viscosity and it deals with the fluid flow velocities relative to the body. The flow velocities are generated by the body motion and by the waves. The former, that is the flow velocities generated by the body motion, create a damping force on the body, which is known as the damping force due to viscosity. In certain cases, such as rolling cylinders in fluid where the pressure force is very small, the fluid force will be dominated by the viscosity force.

The pressure force consists of the hydrostatic restoring force and the hydrodynamic force. The hydrostatic restoring force, F_C, is the force caused by the fluid displaced when the floating body changes its submerged volume. This force usually corresponds linearly to the motion displacement and acts in opposition to it. Therefore, F_C can be written as

$$F_C = -Cs \qquad \text{Eqn.. 5.1}$$

where C = restoring force coefficient, and
s = motion displacement

The hydrodynamic inertial force, F_A, which is created by the hydrodynamic added mass, A, corresponds with the acceleration, s, and opposes the motion. It can be written as

$$F_A = -A\ddot{s} \qquad \text{Eqn. 5.2}$$

where A = hydrodynamic added mass (or mass moment of inertia)

The hydrodynamic velocity force, F_B, is proportional to the velocity, s, and acts in opposition to it. This force resulted from the energy losses of the body due to radiated surface waves and is written as

$$F_B = -B\dot{s} \qquad \text{Eqn. 5.3}$$

where B = hydrodynamic damping per unit velocity

The wave induced force, F_W, is the summation of the incident force, F_I, and the diffracted wave force F_D. This force is also known as the wave exciting force and since, its magnitude varies with time, it is included as follows :

$$F_W = (F_I + F_D)e^{-i\omega t} \qquad \text{Eqn. 5.4}$$

where
$i = \sqrt{-1}$
ω = radian frequency of the incident waves, and
t = time

According to Newton's second law, the sum of the above fluid forces will be balanced by the inertial forces (or moments). F_M is equal to the body mass (or mass moment of inertia) multiplied by the acceleration of the body motion, that is

$$F_M = M\ddot{s} = F_W - F_A - F_B - F_C \qquad \text{Eqn. 5.5}$$

where M = total body mass (or mass moment of inertia)

By substituting Eqns. 5.1 to 5.4 into Eqn. 5.5, the force (or moment) equation becomes

$$M\ddot{s} = F_W - A\ddot{s} - B\dot{s} - Cs$$

or

$$(M + A)\ddot{s} + B\dot{s} + Cs = F_W \qquad \text{Eqn. 5.6}$$

5.2 GENERAL FORMULATION FOR EQUATIONS OF SHIP MOTION

The coordinate system applied in this study is a right handed rectangular coordinate system, as shown in Fig. 5.1. Such coordinate system can be described as follows :

a. Earth fixed axis ($0 - X_0Y_0Z_0$) are fixed with respect to earth. Their origin is located arbitrarily but usually at the calm water surface.

b. Body fixed axis (G - xyz) have their origin at the centre of gravity of the body and are coincident with the intersections of the principal planes of inertia.

c. Space-fixed or mean body axis (0 - XYZ) originate at position of the body centre of gravity and are used to describe the body oscillations. The system is parallel to the earth-fixed ($0 - X_0Y_0Z_0$) system but translates with the ship speed U.

There are several assumptions that should be stated in this analysis so that the solution obtained can be justified. These assumptions include :

a. the exciting forces and moments are assumed to be solely contributed by free surface waves,

b. the wave amplitudes or the wave slopes are assumed to be small,

c. the vessel is operated in an infinitely deep ocean, therefore, no appreciable currents or winds would cancel the linear response assumption, and

d. the submerged parts of the vessel are assumed to be reasonably slender.

Considering these assumptions the six degree of freedom coupled equation of motion for a floating body subject to sinusoidal wave excitation of frequency ω may be expressed in the following manner

$$\sum_{k=1}^{6}\left[\left(M_{jk} + A_{jk}\right)\ddot{s}_k + B_{jk}\dot{s}_k + C_{jk}s_k\right] = F_j \qquad \text{Eqn. 5.7}$$

where

k = mode of motion takes 1, 2, 3, 4, 5 and 6 for the surge, sway, heave, roll, pitch and yaw respectively,

j = mode of excitation and takes the values similar to k for the corresponding modes,

M_{jk} = mass matrix containing the mass, mass moment of inertia and products of inertia of the body,

A_{jk} = added mass matrix containing added mass and added moment of inertia per unit acceleration, which are frequency dependent,

B_{jk} = damping matrix containing damping force and moment of inertia per unit velocity,

C_{jk} = restoring matrix containing restoring force and moment matrix per unit displacement,

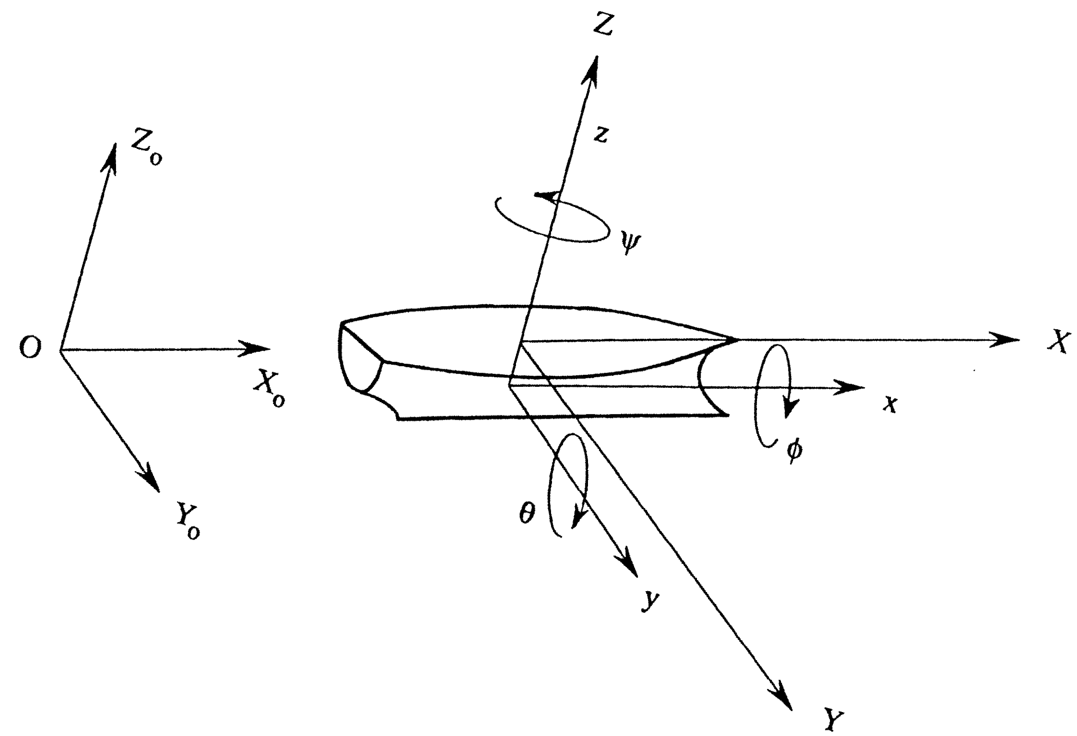


Fig. 5.1 Co-ordinate System for Seakeeping Analysis

s_k = complex motion displacement vector per unit wave amplitude, and

F_j = complex wave exciting force and moment vector per unit wave amplitude.

In some references M_{jk} and s_k that are presented by the index notation as given in Eqn. 5.7, can also be identified according to the initial definition and the corresponding axes defined in Fig. 5.1, as follows :

$M_{11} = M_{22} = M_{33} = M$; that is the mass of the ship

$M_{44}, M_{55}, M_{66} = I_{44}, I_{55}, I_{66}$; that is the mass of inertia in roll, pitch and yaw respectively

$s_1, s_2, s_3, s_4, s_5, s_6 = x, y, x, \phi, \theta, \psi$, that is the motion displacement in the surge, sway, heave, roll, pitch, and yaw respectively.

As the wave exciting force amplitude and moment vector in the right hand side of Eqn. 5.7 is a complex function, so it can be expressed as

$$F_j = \mathrm{Re}(\overline{F}_j e^{-j\omega t}) \qquad \text{Eqn. 5.8}$$

where $\overline{F}_j$ is the complex force amplitude which can be written in terms of the real (R) and the imaginary (I) part as

$$\overline{F}_j = F_{jR} + iF_{jI} \qquad \text{Eqn. 5.9}$$

By substituting Eqn. 5.9 into Eqn. 5.8, it can be found that

$$F_j = \left(F_{jR} + iF_{jI}\right)e^{-i\omega t}$$

or

$$F_j = F_{jR}\cos\omega t + F_{jI}\sin\omega t \qquad \text{Eqn. 5.10}$$

and Eqn. 5.10 can be written as

$$F_j = |F_j|\cos(\varepsilon_j - \omega t) \qquad \text{Eqn. 5.11}$$

where

$$|F_j| = \sqrt{\left(F_{jR}^2 + F_{jI}^2\right)} \qquad \text{Eqn. 5.12}$$

= maximum of the wave exciting force, and

$$\varepsilon_j = \arctan(F_{jI} / F_{jR}) \qquad \text{Eqn. 5.13}$$

= the phase shift of the maximum of the wave exciting force from the incident wave at the origin of the wave coordinate system

To be compatible with the complex expression of F_j, the motion displacement s_k is also assumed to be complex function and can be expressed as

$$s_k = \mathrm{Re}(\bar{s}_k e^{-i\omega t}) \qquad \text{Eqn. 5.14}$$

Furthermore, the velocity and the acceleration components can be expressed as

$$\dot{s}_k = -i\omega \bar{s}_k e^{-i\omega t} \qquad \text{Eqn. 5.15}$$

$$\ddot{s}_k = -i\omega^2 \bar{s}_k e^{-i\omega t} \qquad \text{Eqn. 5.16}$$

Following similar sequence from Eqns. 5.8 up to 5.13, the motion displacement can also be written as follows :

$$\bar{s}_k = s_{kR} + i s_{kI} \qquad \text{Eqn. 5.17}$$

$$s_k = s_{kR}\cos\omega t + s_{kI}\sin\omega t \qquad \text{Eqn. 5.18}$$

$$|s_k| = \sqrt{(s_{kR}^2 + s_{kI}^2)} \qquad \text{Eqn. 5.19}$$

$$\alpha_k = \arctan(s_{kI} / s_{kR}) \qquad \text{Eqn. 5.20}$$

$$s_k = |s_k|\cos(\alpha_k - \omega t) \qquad \text{Eqn. 5.21}$$

where

$|s_k|$ = the maximum of the motion displacement, and

α_k = the phase shift of the maximum of the motion displacement from the maximum of the incident wave at the origin of the wave coordinate system.

Detail solutions to the equations of motion are given in Appendix B. For all sections use has been made of the Lewis transformation to determine sectional added mass and damping.

5.3 SHIP MOTION IN IRREGULAR WAVES

The mathematical approach predicting ship motions in irregular seas was put forward by *Weinblum* and *St. Denis* [16]. Based on the work associated with random analysis in other fields and the study of actual ocean waves [22], the spectral analysis of sea waves and ship motions was then extensively advanced by *St. Denis* and *Pierson* [17].

There are a number of different wave energy spectrum formulations that can be derived from wave data. The wave spectra in most common usage include two deep water (fully arisen and fetch unlimited) spectra and one fetch-limited spectra. Formula relating to a family of spectral forms is given in Appendix B.

For a fully aroused sea, one of the most commonly used energy spectrum formula is the *Pierson-Moskowitz* wave spectra [18], which belongs to the deep water spectra. Such spectra is also well recognised as the wind speed spectra since wind speed is included directly in the spectral density function. The *P-M* wave spectra is formulated as

$$S(\omega) = \frac{\alpha g^2}{\omega} \exp\left[-\beta\left(\frac{g}{U_{19.5}\,\omega}\right)^4\right] \qquad \text{Eqn. 5.22}$$

where

$S(\omega)$ = spectral density (m^2s),

ω = wave frequency (rad/s),

$\alpha \quad = 8.10 \times 10^{-3}$,

$\beta \quad = 0.74$,

$U_{19.5}$ = wind velocity at 19.5 m above the calm water surface (m/s)

Two other wave spectrum formulations for fully developed seas which are quite frequently used are *Bretschneider* and ITTC/ISSC'75 formulations. The Bretschneider [19] spectrum takes form

$$S(\omega) = \frac{1.25}{4} \frac{\omega_m^4}{\omega^5} \zeta_{1/3}^2 \exp\left[-1.25\left(\frac{\omega_m}{\omega}\right)^4\right] \qquad \text{Eqn. 5.23}$$

where

ω_m = modal wave frequency (rad/s)

$\zeta_{1/3}$ = significant wave height (m)

The spectral formulation recommended by the International Towing Tank Conference (ITTC) and the International Ship Structures Congress (ISSC) was derived by *Mirokhin* and *Kholodilin* [23], having the form,

$$S(\omega) = \frac{A}{\omega^5} \exp(-B / \omega^4) \qquad \text{Eqn. 5.24}$$

where

$A \quad = (8.10 \times 10^{-3})g^2$, and

$B \quad = (3.11 \times 10^4)/\zeta_{1/3}^2$ for $\zeta_{1/3}$ in m

Another well known spectral formulation which is of fetch limited type recommended by ITTC in 1984 is one proposed by JONSWAP (Joint North Sea Wave Project) [24]. The formulation of this spectrum is

$$S(\omega) = 155 \frac{\zeta_{1/3}^2}{T_1^4 \omega^5} \exp\left(\frac{-944}{T_1^4 \omega^4}\right) (3.3)^Y \qquad \text{Eqn. 5.25}$$

where

$$Y = \exp\left[\frac{0.191\omega T_1 - 1}{\sigma\sqrt{2}}\right]^2 \qquad \text{Eqn. 5.26}$$

and $\sigma = 0.07$ for $\omega \leq 5.24/T_1$

$\sigma = 0.09$ for $\omega > 5.24/T_1$

Other characteristic periods below can be used in this formulation,

$$T_1 = 0.924T_{-1} = 0.834T_0 = 1.073T_2$$

where

T_{-1} = the energy average period, $2\pi m_{-1} / m_0$

T_0 = the modal period, $2\pi / \omega_0$ where ω_0 is the frequency of the spectrum peak

T_1 = the average period $2\pi m_0 / m_1$

T_2 = the average zero crossing period, $2\pi\sqrt{\frac{m_0}{m_2}}$

The response spectrum is calculated by taking into account the response amplitude operator

$$S_m(\omega) = \left[\frac{m_A}{\zeta_A}\right]^2 S(\omega) \qquad \text{Eqn. 5.27}$$

where

$S_m(\omega)$ = spectral density of ship response for any mode of motion (m^2s for heave or deg^2s for pitch and roll),

m_A = motion amplitude (m or deg), and

ζ_A = wave amplitude (m)

From a known spectrum, one can then obtain wave and motion characteristics amplitudes by using simple formulations given in Table 5.1.

Table 5.1 Wave and Motion Amplitudes

Average Amplitudes	$1.25\,(m_0)^{0.5}$
Significant Amplitudes	$2.00\,(m_0)^{0.5}$
Average of 1/10 Highest Amplitudes	$2.55\,(m_0)^{0.5}$
Average of 1/100 Highest Amplitudes	$3.34\,(m_0)^{0.5}$

where m_0 = moment area under the spectrum (see Appendix B).

Since the formulations in this table are derived for narrow frequency spectrum (that is, Rayleigh distribution of the wave height histogram), then a correction factor has been introduced for response spectrum as

$$CF = \sqrt{(1-\varepsilon^2)} \qquad \text{Eqn. 5.28}$$

where

ε = the broadness parameter which is found from the even moments of the spectrum (see Appendix B).

The JONSWAP wave spectrum will be used thoughout this study for the analysis of offshore supply vessels in irregular seas.

However, if a ship is in transit at speed U at an angle β to the predominant direction of the waves, then it will encounter the waves at a frequency different from that which it would meet if it were at rest. The encounter frequency is rewritten as

$$\omega_e = \omega - \frac{U\omega^2}{g}\cos\beta \qquad \text{Eqn. 5.29}$$

The energy of the wave is the same whether it is expressed in term of ω or ω_e, so that

$$E_W\left[\zeta^2\right] = \int_0^\infty S(\omega)d\omega = \int_0^\infty S(\omega_e)d\omega_e \qquad \text{Eqn. 5.30}$$

where

$$S(\omega_e) = \frac{S(\omega)}{\left|d\omega_e / d\omega\right|} \qquad \text{Eqn. 5.31}$$

The modulus of $d\omega_e / d\omega$ is used because $S(\omega_e)$ must always be positive. By deriving the definition of encounter frequency, one can obtain

$$S(\omega_e) = \frac{S(\omega)}{\left|1 - \dfrac{2U\omega}{g}\cos\beta\right|} \qquad \text{Eqn. 5.32}$$

Given the wave spectrum $S(\omega)$, it is thus possible to find the wave encounter spectrum, $S(\omega_e)$. This effect is to distort the spectrum while the area under the curves remains constant.

5.4 COMPUTER PROGRAM FOR SEAKEEPING ANALYSIS

The computer program to assess the seakeeping characteristics of the offshore supply vessels forms part of an integrated computer program for the preliminary design of such vessels. The input data required to run the program are as follows :

a. main parameters such as length, beam, depth, and draught,

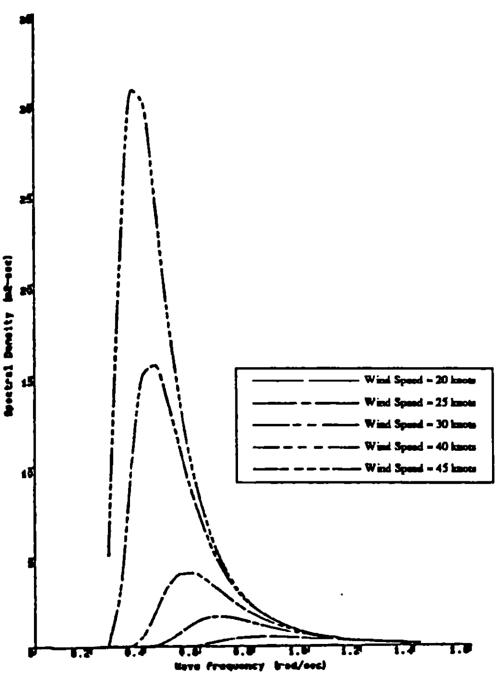
b. displacement and midship coefficient,

c. speed of vessel,

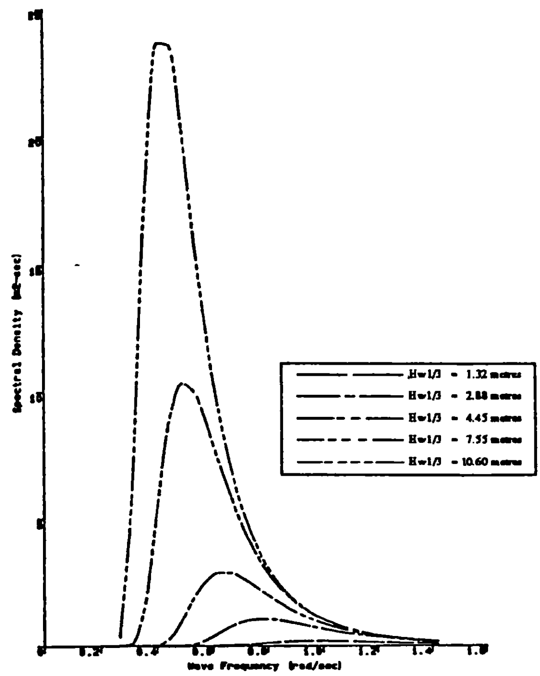
d. initial stability of vessel, and

e. offset data for alternate stations starting from the after perpendicular to the forward perpendicular, from the bottom of keel right to the design waterline.

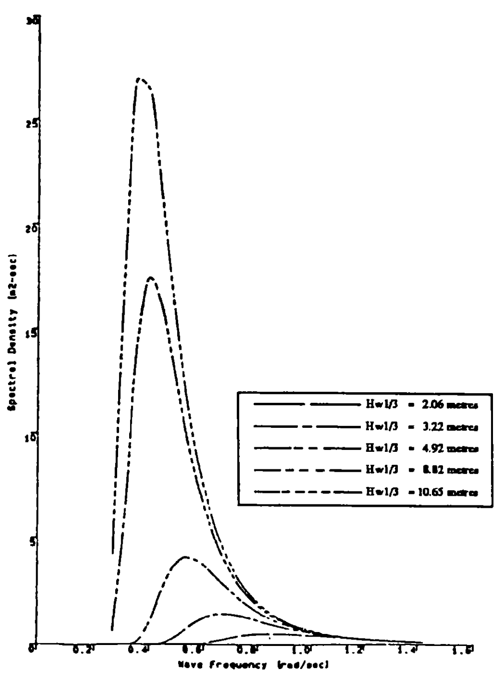
f. significant wave height, wave period and angle of wave propagation whether beam sea, quartering sea or head sea.



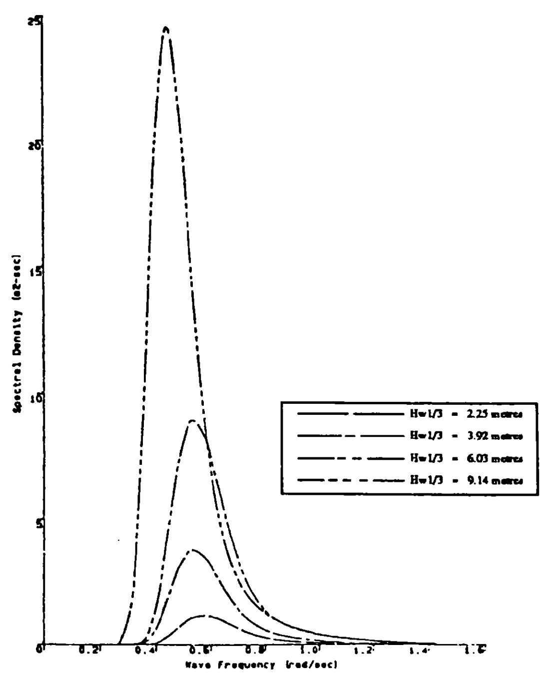
Pierson - Moskowitz Wave Spectrum



Breitschneider Wave Spectrum



ITTC/ISSC 1975 Wave Spectrum



JONSWAP Wave Spectrum

Fig. 5.2 Various Plots of Wave Spectrum

Once the above input data is available, the program will evaluate the inertial, damping, restoring and exciting coefficients for heave, pitch and roll. The user will be provided with the first output of the program, that is, the responses for heave, pitch and roll for regular sea conditions.

The program will proceed with the evaluation of wave spectrum using the JONSWAP spectrum formulation and this wave spectrum is later transformed into a spectrum where the frequency of encounter is considered instead of the absolute wave frequency. The motion amplitude spectrum is obtained by multiplying the ordinates of the transformed wave spectrum by the ordinates of the ratio amplitude operator for the corresponding frequencies of encounter.

Finally, the area under the motion amplitude is determined in order to obtain the necessary motion characteristics such as average, average of one-third highest, average of one-tenth highest motion amplitudes and the corresponding velocity and acceleration using the formulation given in Appendix B. Details of the computer program is given in the flowchart in Fig. 5.3.

5.5 DISCUSSION OF RESULTS

5.5.1 Motion In Regular Sea Condition

Samples of output from the computer program based on an existing supply vessel working in the North Sea region for regular sea conditions are given in Fig 5.4 to Fig 5.9. The figures shown are of non-dimensional motion responses versus non-dimensional frequency. The non- dimensional responses of translational motion such as heaving can be simply determined by

$$Y'_{z\zeta} = \frac{z_A}{\zeta_A} \qquad \text{Eqn. 5.33}$$

where

$Y'_{z\zeta}$ = non-dimensional heave response

z_A = heave amplitude (m), and

ζ_A = wave amplitude (m)

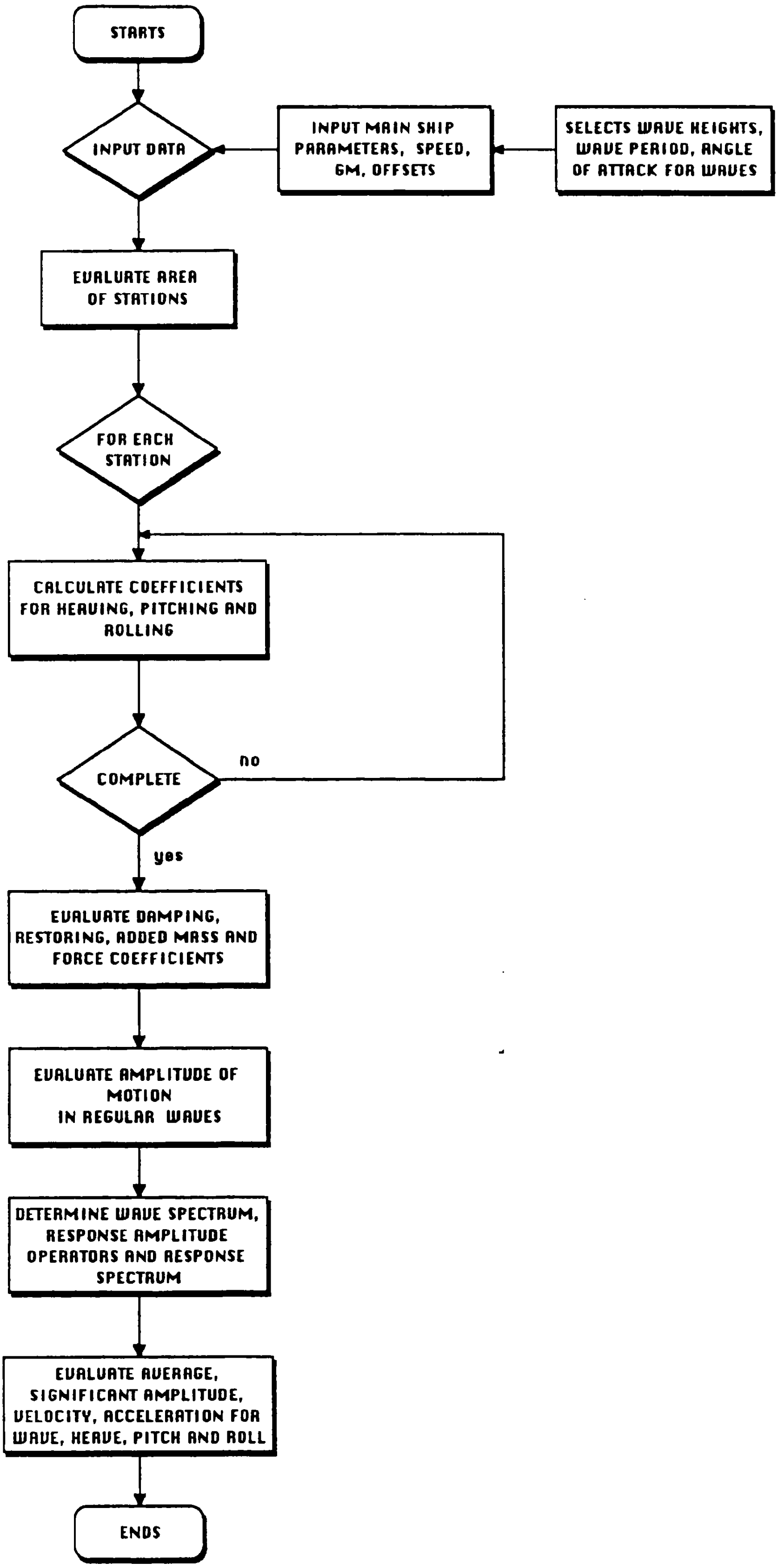


Fig. 5.3 Program Flowchart for Seakeeping Analysis

In order to non-dimensionalise the rotational motion responses, the wave number, which takes into account the wave frequency and the acceleration due to gravity, should be included in the calculation, as given by

$$Y'_{\phi\zeta} = \frac{\phi_A}{\zeta_A \omega^2 / g}$$ Eqn. 5.34

$$Y'_{\theta\zeta} = \frac{\theta_A}{\zeta_A \omega^2 / g}$$ Eqn. 5.35

where

$Y'_{\phi\zeta}$ = non-dimensional roll angle,
$Y'_{\theta\zeta}$ = non-dimensional pitch angle,
θ_A = roll amplitude (rad), and
ϕ_A = pitch amplitude

The non-dimensionalisation of the wave frequency is taken as

$$\omega' = \frac{\omega}{\sqrt{g/L}}$$ Eqn. 5.36

where L is the length of vessel.

Based on the figures plotted, the heave responses are quite significant compared to pitch and roll responses for beam sea at zero forward speed, quartering sea at zero forward speed, and head sea with or without forward speed. This is due to the fact that such a vessel has a high exciting force coefficient for heaving.

5.5.2 Motion in Irregular Sea Condition

Figure 5.10 and Figure 5.11 show the response spectrum for amplitude, velocity and acceleration for heaving and pitching motion for various significant wave heights for an existing offshore supply vessel operating in the irregular condition of the North Sea. Figure 5.12 shows the graphical relationships between the significant double motion amplitude of the vessel proceeds irregular beam waves and the significant wave height.

For motions in irregular waves, as expected, the higher the wave amplitude, the more significant the amplitude, velocity and acceleration responses of the vessel will be. The peak values for such a vessel seems to fall between a wave frequency of 0.4 to 0.6 rad/s.

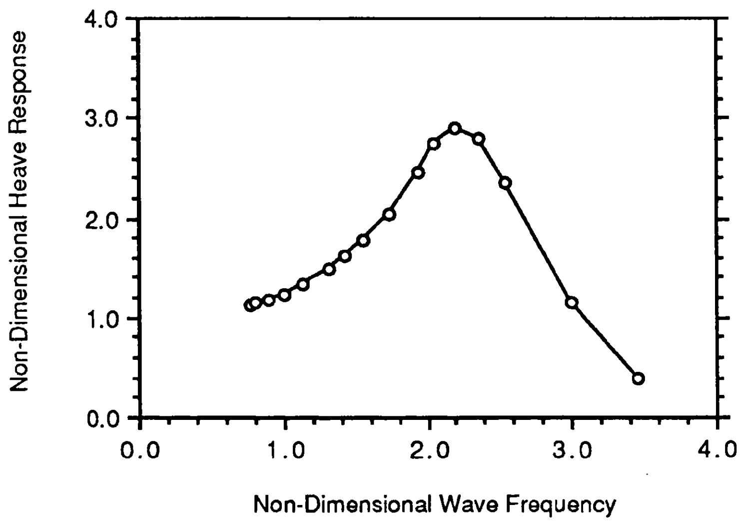


Fig. 5.4a Heave Response for Beam Sea at Zero Forward Speed

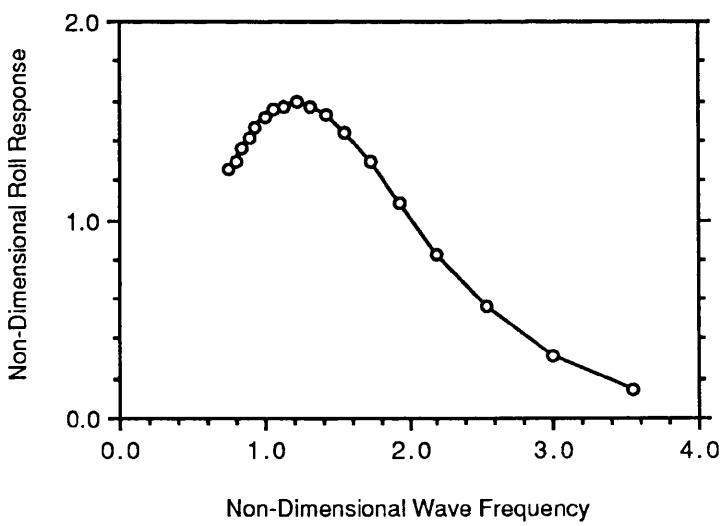


Fig. 5.4b Roll Response for Beam Sea at Zero Forward Speed

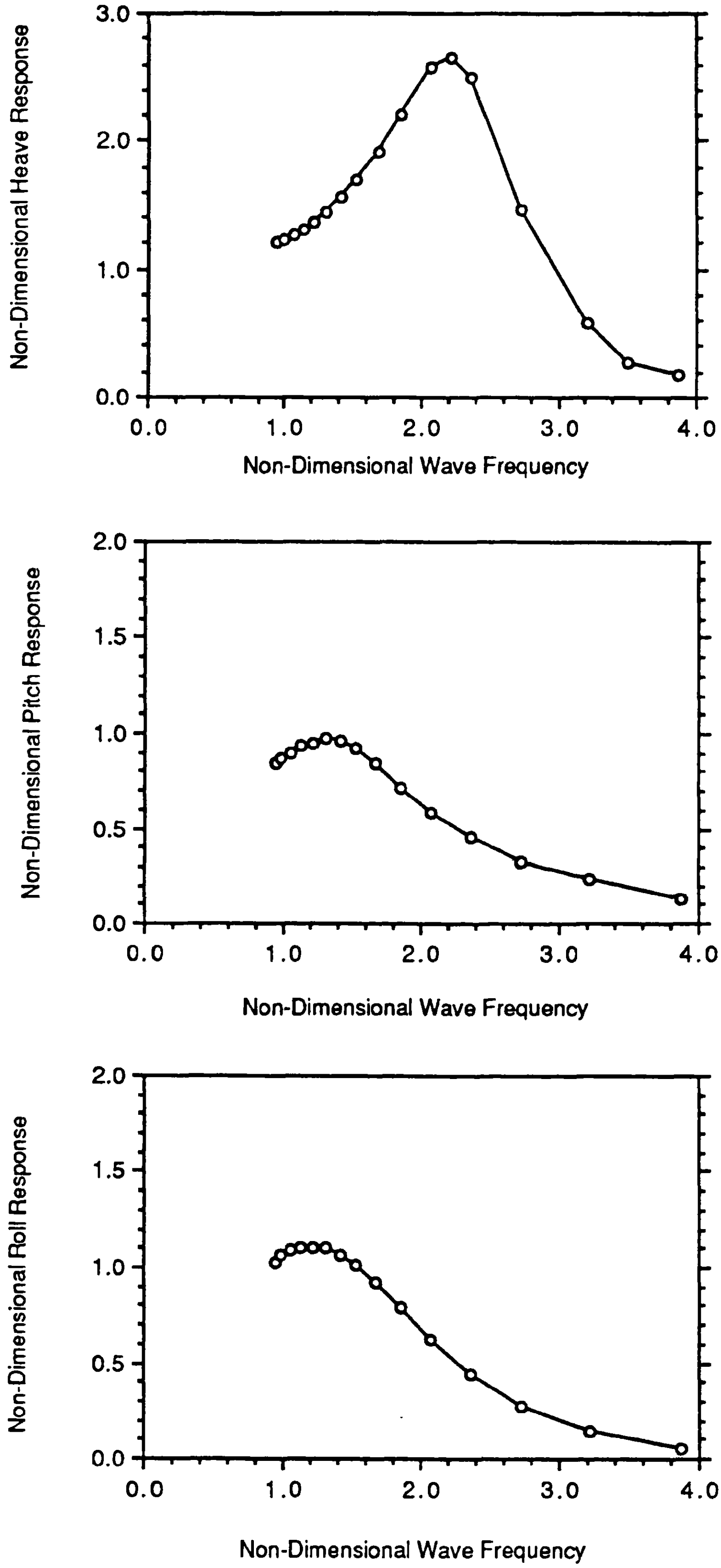


Fig. 5.5 Responses for Quartering Sea at Zero Speed

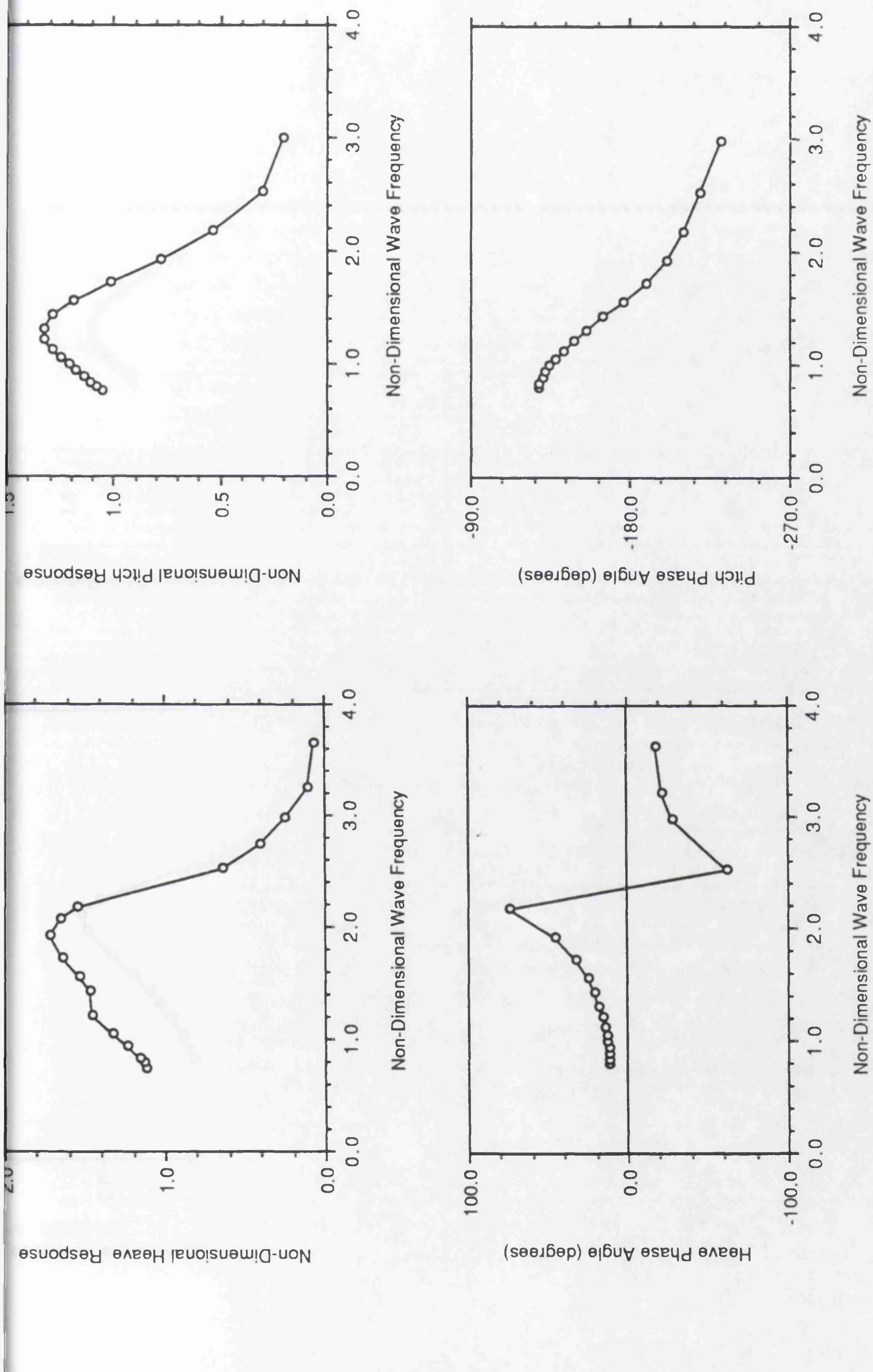


Fig. 5.6 Responses for Head Sea at Zero Forward Speed

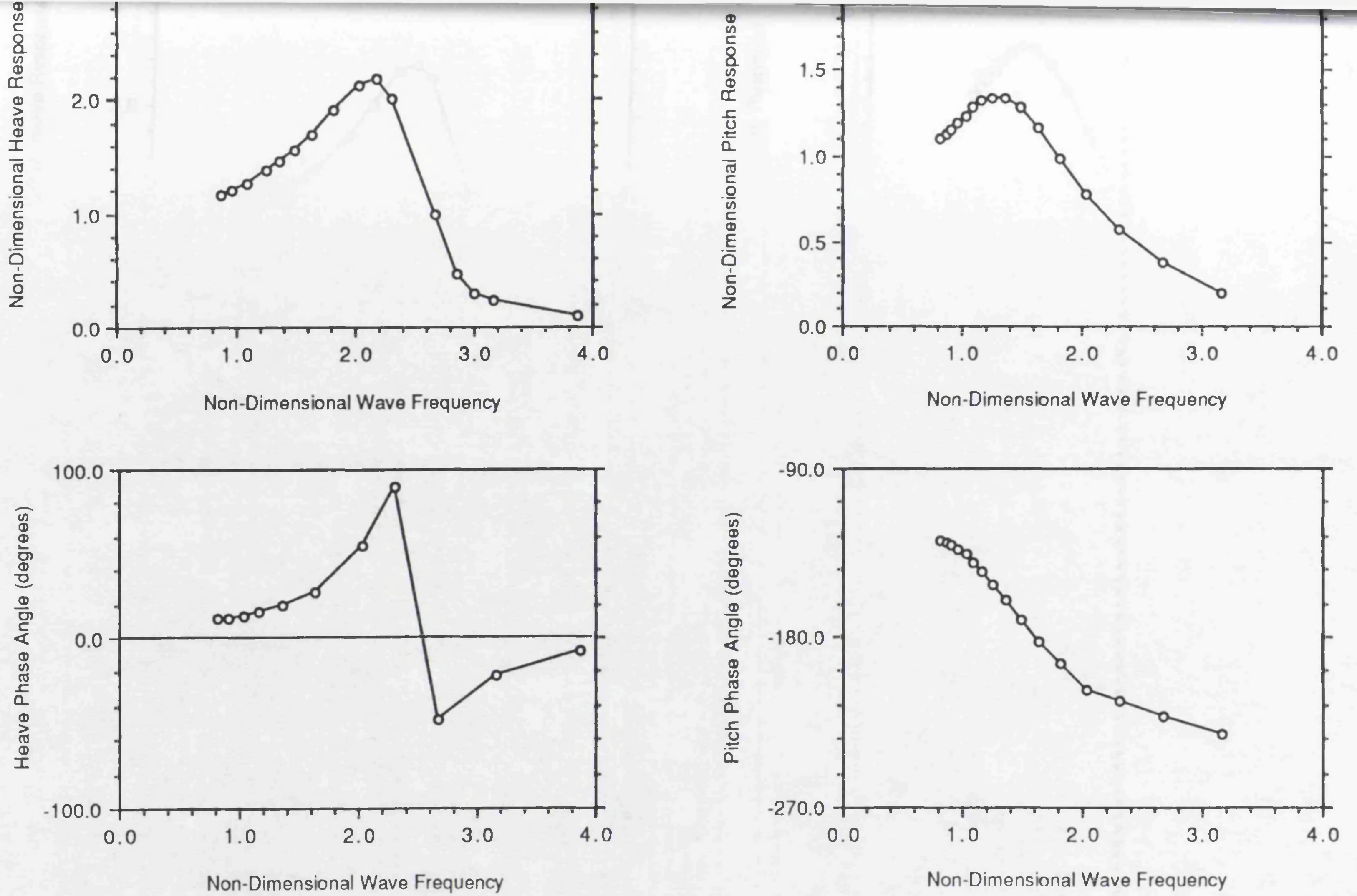


Fig. 5.7 Responses for Head Sea at 5 Knots

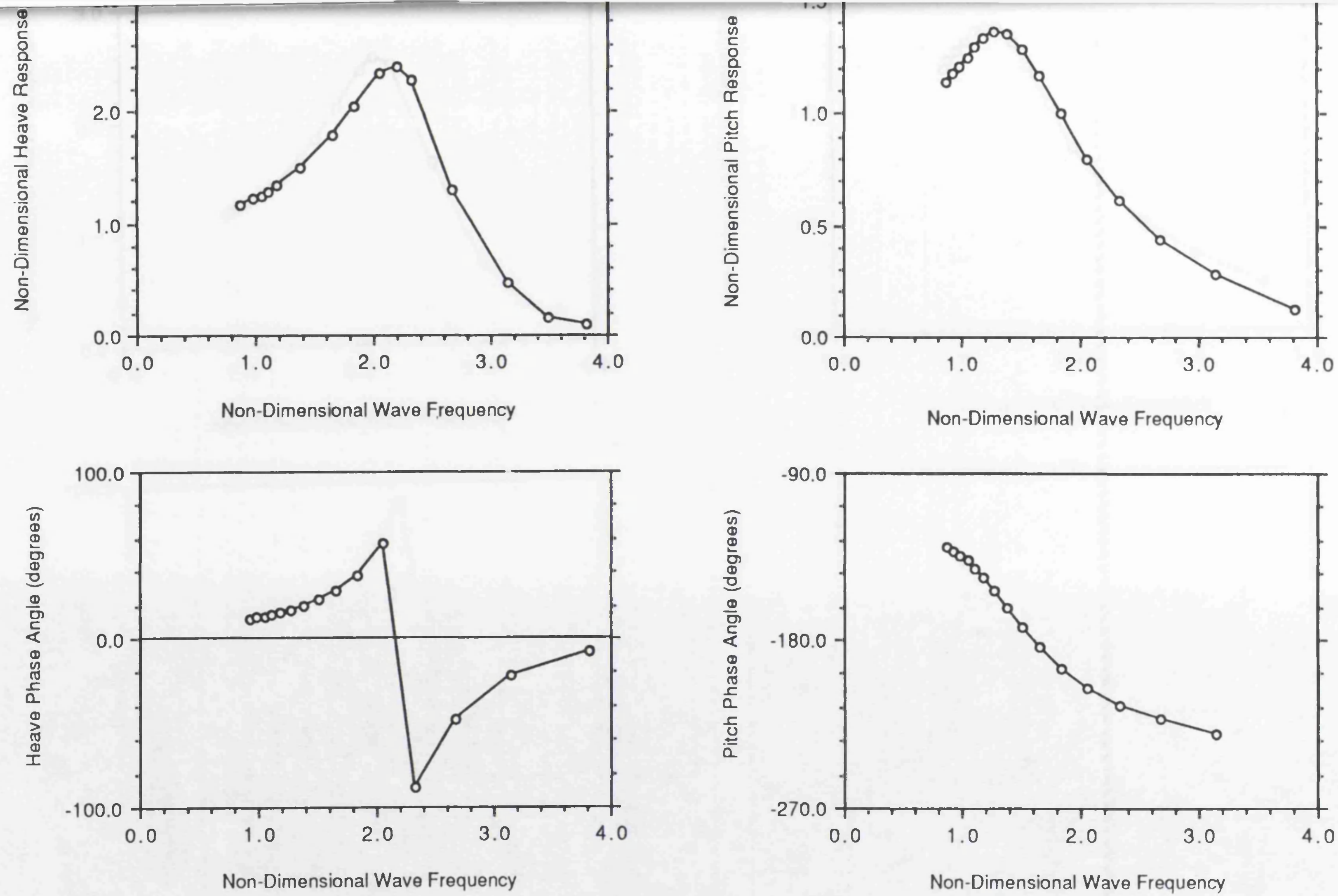


Fig. 5.8 Responses for Head Sea at 10 Knots

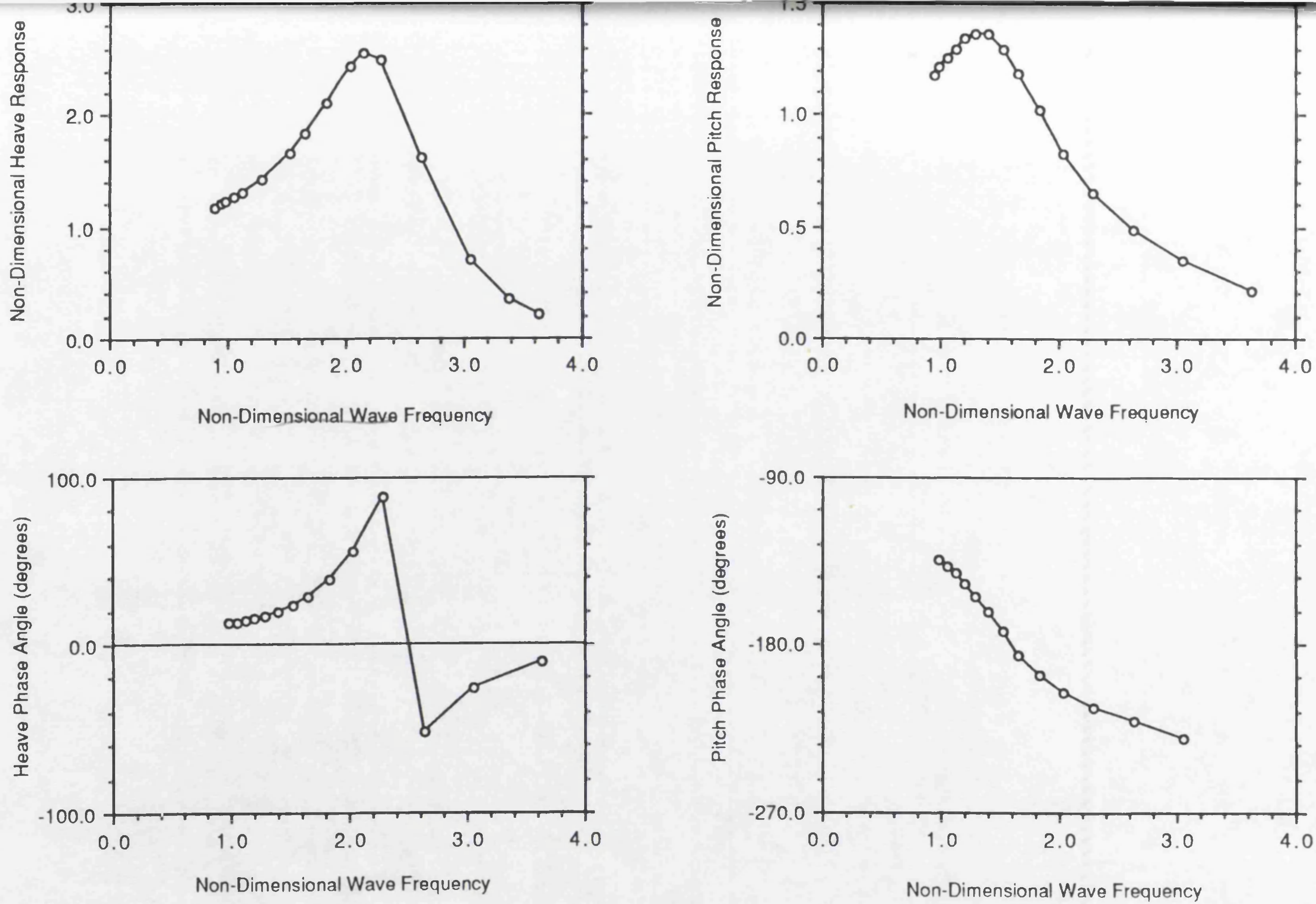


Fig. 5.9 Responses for Head Sea at 15 Knots

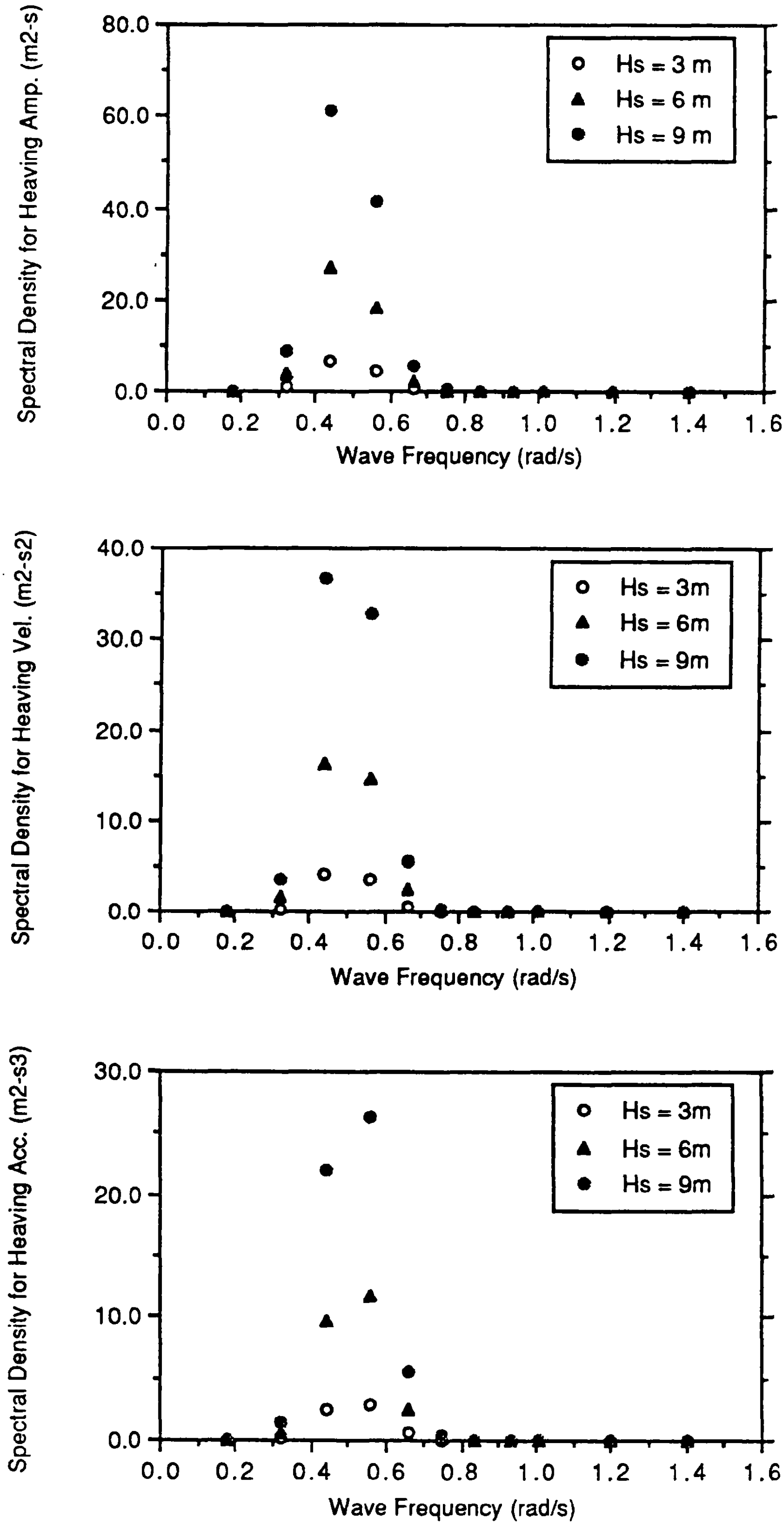


Fig. 5.10 Heaving Amplitude, Velocity and Acceleration for Head Sea at Different Significant Wave Height

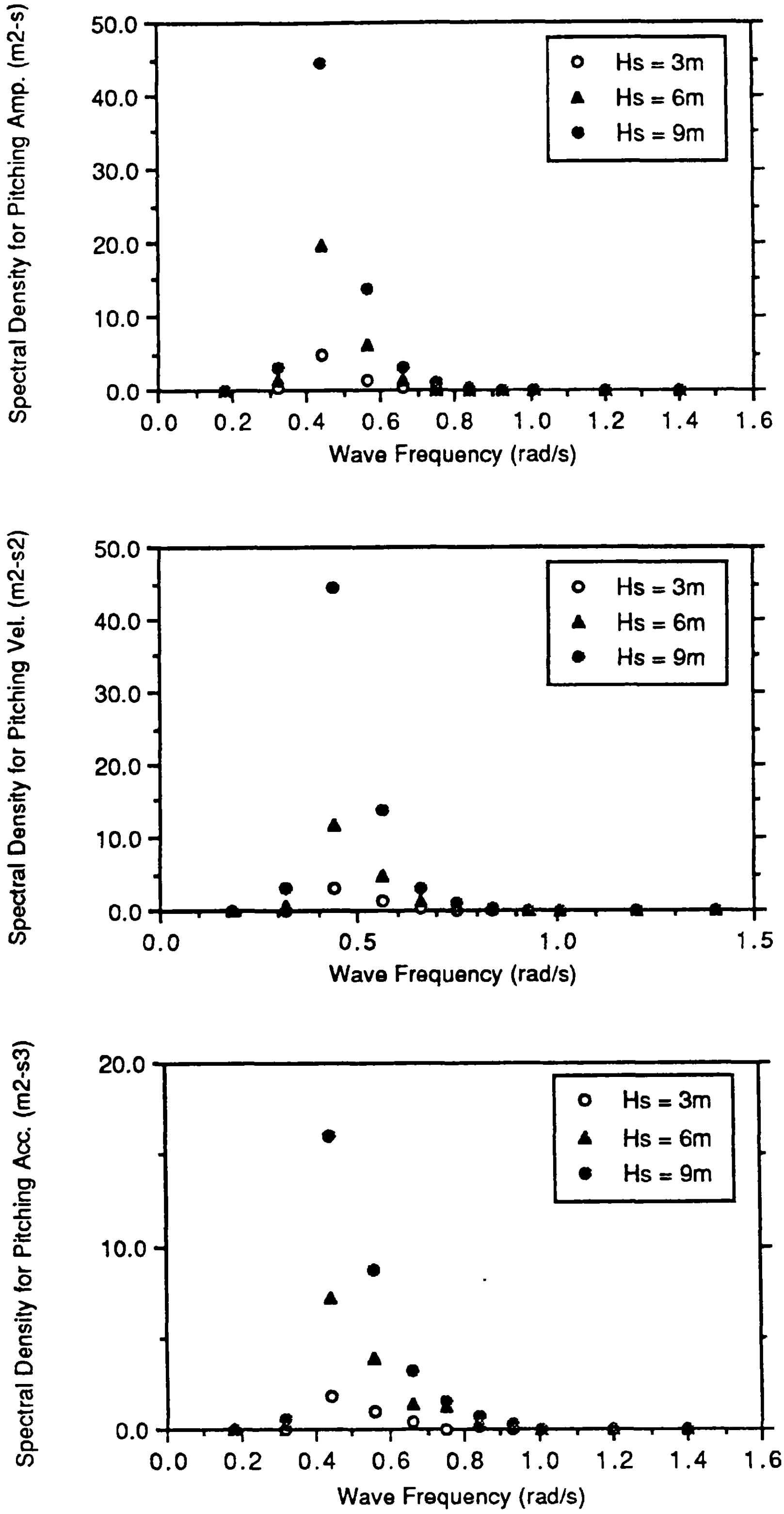


Fig. 5.11 Pitching Amplitude, Velocity and Acceleration for Head Sea at Different Significant Wave Height

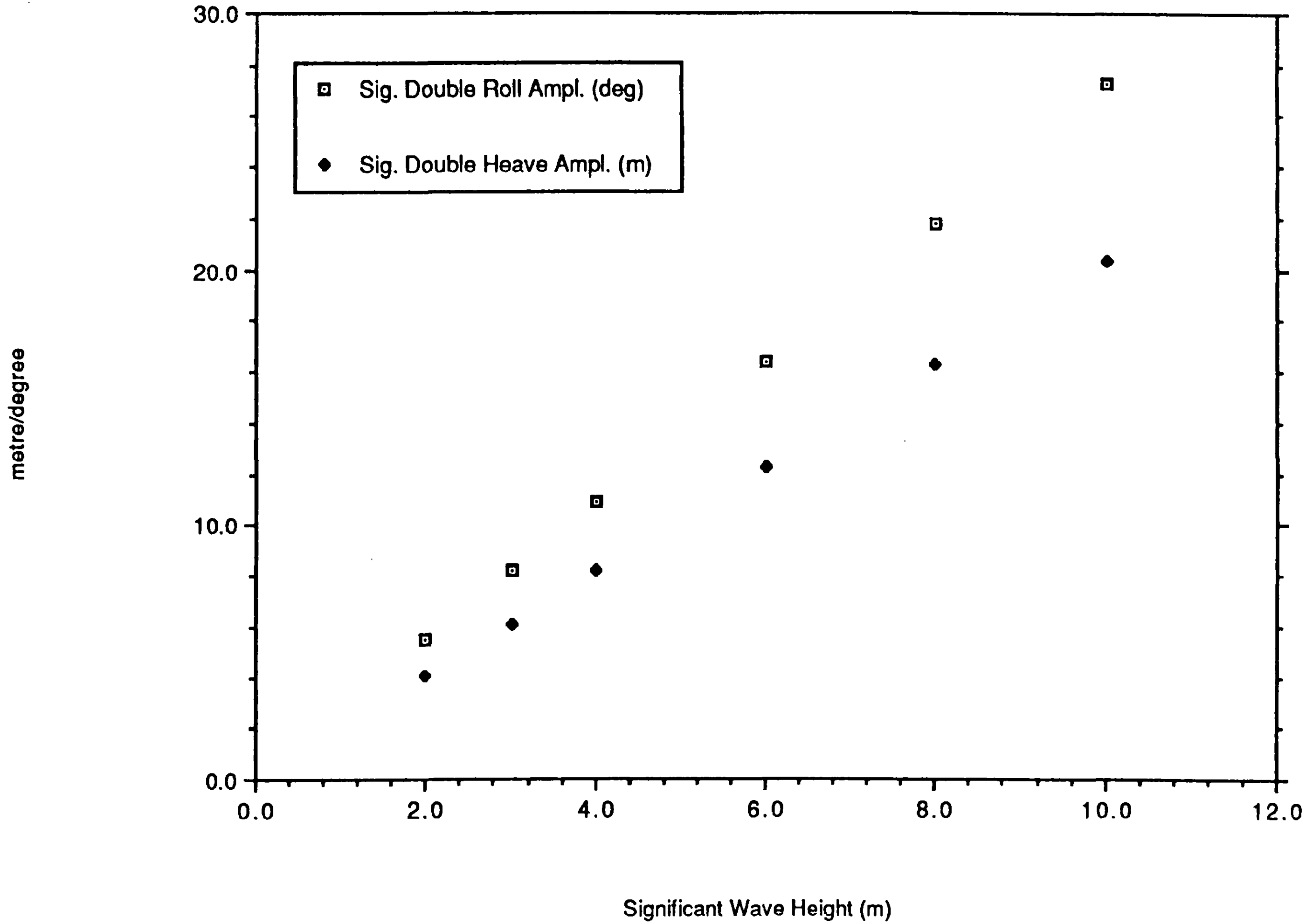


Fig. 5.12 Double Heave and Roll Amplitude for Different Significant Wave Heights

5.6 SEAKEEPING MERIT RATING CRITERIA

As a result of seakeeping theory developments to determine the performance of vessels in rough seas, the fair agreement between experimental and theoretical findings seems to indicate that such programs might also be useful for preliminary design since they provide the naval architect with a valid tool for classification of his design based upon the vessel's seakeeping capability in bad weather conditions.

The following steps therefore involve the utilisation of these calculation tools to formulate a judgement about the basic seakeeping qualities which the vessel should have, at its design stage, in order to provide the naval architect with an objective evaluation element so that he may choose from various alternative solutions. This evaluation criterion has to be based upon certain considerations such as follows :

a. a judgement on the seakeeping capacity of a ship must take into account various phenomena which somehow or other might curtail or prevent its operational performance,

b. such a judgment cannot be based on one single sea state, but has to consider the aggregate conditions of the sea which the vessel may encounter during its life,

c. it should be possible to work out this calculation and to determine the merit rating of the vessel, taking into account that only a few elements are available at the initial design stage.

In this study, the seakeeping criteria to evaluate the offshore supply vessel performance in irregular seas (Table 5.2) are adopted from [21]. However, not all of these criteria will be evaluated on such vessels due to the limitation of investigation. Some of the criteria from Table 5.2 that will be used herein is relisted in Table 5.3.

The values obtained from the computer program are then observed by using two matrices as shown in Table 5.4 to determine the seakeeping qualities of the offshore supply vessels. The first matrix contains codes according to the above criteria as a function of the vessel speed and heading of the seas. The second matrix indicates the significant wave height at which the specified criterion in the first matrix is being exceeded.

Table 5.2 Typical Seakeeping Criteria for Conventional Ships

No.	Criteria
1	12^{o} single amplitude average roll.
2	3^{o} single amplitude average pitch.
3	Motion sickness indicator (20% of laboratory subjects experience nausea within two hours).
4	Significant heave acceleration $\leq 0.4g$ (no people on deck).
5	Significant heave acceleration $\leq 0.2g$ (people on deck).
6	Bottom plate damage.
7	Three slams in 100 motion cycles.
8	One deck wetness every two minutes.

Table 5.3 Seakeeping Criteria for Offshore Supply Vessels

No.	Criteria
1	12^{o} single amplitude average roll.
2	3^{o} single amplitude average pitch.
3	Significant heave acceleration $\leq 0.4g$ (no people on deck).
4	Significant heave acceleration $\leq 0.2g$ (people on deck).

Table 5.4 Seakeeping Qualities of Offshore Supply Vessels

SHIP SPEED (knots)	BEAM SEA 90°	QUAR. SEA 135°	HEAD SEA 180°
0.0	4 or 3	4 or 2	4 or 2
5.0	-	-	2
10.0	-	-	3
15.0	-	-	3
SHIP SPEED (knots)	**ACCEPTABLE SIGNIFICANT WAVE HT. (metres)**		
0.0	2.49/5.96	3.48/6.23	3.67/5.34
5.0	-	-	4.98
10.0	-	-	5.24
15.0	-	-	5.13

Table 5.5 Wave Scatter for the North Sea Region (Summer)

SIGNIFICANT WAVE HEIGHT (metres)	WAVE PERIOD (seconds)			
	$T \leq 7$	$8 \leq T \leq 9$	$10 \leq T \leq 11$	$12 \leq T$
$0.00 \leq z \leq 0.75$	0.12	0.00	0.00	0.00
$0.75 \leq z \leq 1.75$	0.37	0.06	0.01	0.01
$1.75 \leq z \leq 2.75$	0.15	0.09	0.03	0.01
$2.75 \leq z \leq 3.75$	0.04	0.03	0.02	0.00
$3.75 \leq z \leq 5.75$	0.01	0.02	0.01	0.01
$5.75 \leq z \leq 7.75$	0.00	0.00	0.00	0.00
$7.75 \leq z \leq 9.75$	0.00	0.00	0.00	0.00

Table 5.6 Wave Scatter for the North Sea Region (Winter)

SIGNIFICANT WAVE HEIGHT (metres)	WAVE PERIOD (seconds)			
	$T \leq 7$	$8 \leq T \leq 9$	$10 \leq T \leq 11$	$12 \leq T$
$0.00 \leq z \leq 0.75$	0.03	0.00	0.00	0.00
$0.75 \leq z \leq 1.75$	0.15	0.03	0.01	0.01
$1.75 \leq z \leq 2.75$	0.13	0.10	0.04	0.02
$2.75 \leq z \leq 3.75$	0.06	0.07	0.05	0.03
$3.75 \leq z \leq 5.75$	0.02	0.05	0.06	0.04
$5.75 \leq z \leq 7.75$	0.01	0.02	0.02	0.02
$7.75 \leq z \leq 9.75$	0.00	0.00	0.00	0.02

The box scores is composed making use of the information from the seakeeping criteria and the wave height distributions of a certain area where the vessel will be operated. In the case of offshore supply vessel, information is obtained from Table 5.5 and Table 5.6, which is the distribution data of the North Sea. Information that can be drawn from the box scores is the percentage of time the vessel could be expected to operate in its environment without violating the specified criteria.. The box scores of offshore supply vessel as shown in Table 5.7 is calculated by assuming that the probability of encountering a sea at a specific heading angle relative to the vessel is equally likely for the three headings.

The numbers presented in Table 5.7 reflect the proportion of time that the offshore supply vessel could be operated effectively in the North Sea. On the hand the values of one minus the numbers in the box scores are the proportion of time that the operation of such vessel is degraded due to motion in a certain season. A similar procedure can be applied to assess the duration of effective operation and down time of the vessel in a whole year when the information of one year wave distributions in a specific area is available. Such presentation is given in [109].

Table 5.7 Seakeeping Box for OSV Operating in North Sea

General Criteria	Summer	Winter
1 - 4	0.89	0.63

5.7 CONCLUSION

The conclusions of the study in this chapter are set out below :

1. A brief evaluation of the offshore supply vessels seakeeping qualities through the seakeeping criteria and the box scores revealed the high capability of such vessel to overcome the motion problem in a harsh environment. If it is assumed that the wave distribution given in Table 5.5 and 5.6 represents the extreme minimum and maximum values of a whole year in the North Sea, box scores of all year can then be added as given in Table 5.8.

Table 5.8 Seakeeping Box for OSV Operating in North Sea (all year)

General Criteria	Summer	Winter	All Year
1 - 4	0.89	0.63	0.76

2. Spectral analysis is the most suitable method in the design process to predict the behaviour of a ship motion in irregular seas. The accuracy of the predictions is dependent on the quality of information regarding the sea properties where the ship will be operated and the criteria used.

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CHAPTER 6

MANOEUVRING CHARACTERISTICS

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MANOEUVRING CHARACTERISTICS

6.0 INTRODUCTION

Manoeuvring characteristics of ships are complex phenomena which include course keeping and turning ability. There are no simple criteria to rate the qualities of ships with respect to these characteristics. The associated flow phenomena are complex and often coupled to other phenomena. Course keeping in waves, for instance, is often connected to rolling motion stability. Further complications are introduced by the environment (shallow water, bank effects, other traffic), the actual operating conditions of the ship and human aspects.

Manoeuvring characteristics have often been neglected during the preliminary design phase. Recently, an increased awareness of the importance of manoeuvrability for the safety of the ship and environment can be observed. Accidents such as with 'Herald of Free Enterprise', in which manoeuvrability played some role, have certainly contributed to this increased interest [25]. Recognition of the importance of knowledge on the manoeuvring characteristics has for instance led to IMO requirements for posting data on the characteristics at the navigating bridge of ships. In addition, it is expected that IMO will issue criteria for ship manoeuvrability in the near future.

The rudder design and consequent influence on manoeuvrability of offshore supply vessels is perhaps nearly as important as the selection of the proper engines and the propeller design. An offshore supply vessel, unlike other vessels, is called upon to perform unusual operations, such as turning a tow, many times its length and displacement, efficiently and in minimum possible radius under adverse wind and weather conditions. As a result of these peculiar requirements, many different and peculiar rudder types for such vessels have been developed and in an effort to increase manoeuvrability as much as possible, the ratio of rudder area to the lateral plane area is unusually high. Supply vessel rudders are usually spade types and have an area about 2.5 to 5% of the immersed midline plane area. They may be enhanced with flaps.

In this study, a computer program to evaluate the manoeuvring characteristics of offshore supply vessels is developed based on empirical formulae obtained from previous researchers.

6.1 EQUATIONS OF MOTION

In this analysis, the ship is considered to be a rigid body, with only three degrees of freedom, that is, surge, sway and yaw. The ship motions in the other three degrees of freedom, roll, pitch and heave, are neglected and not considered in this treatment. It is convenient to describe the motions in terms of a Eulerian system of axes coincident with amidship. This co-ordinate system is illustrated in Fig. 6.1 together with the basic nomenclature used. Thus, this gives rise to the equations of motion :

$$X = m(\dot{u} - rv - x_G r^2) \qquad \text{Eqn. 6.1}$$

$$Y = m(\dot{v} + ur + x_G \dot{r}) \qquad \text{Eqn. 6.2}$$

$$N = I_Z \dot{r} + m x_G (\dot{v} + ru) \qquad \text{Eqn. 6.3}$$

In the above equation, the terms on the right hand side describe the inertial responses and those on the left hand side are the hydrodynamic forces and moments acting on the ship due to the motions which are usually expressed as perturbations about a steady ahead speed. These forces and moments are then assumed to be directly proportional to these perturbation quantities. Details of this procedure and its limitations are given in References [2] and [22].

Neglecting the non-dimensional terms, Eqn. 6.1 to Eqn. 6.3 may be expressed as :

$$X = X_{\dot{u}}\dot{u} + X_u \Delta u \qquad \text{Eqn. 6.4}$$

$$Y = Y_{\dot{v}}\dot{v} + Y_v v + Y_{\dot{r}}\dot{r} + Y_r r \qquad \text{Eqn. 6.5}$$

$$N = N_{\dot{v}}\dot{v} + N_v v + N_{\dot{r}}\dot{r} + N_r r \qquad \text{Eqn. 6.6}$$

In all the terms in the above equations, the subscript notation refers to partial differentials with respect to that variables. For example

$$X_{\dot{u}} = \frac{\partial X}{\partial \dot{u}} \qquad \text{and} \qquad Y_v = \frac{\partial Y}{\partial v}$$

Expressing Eqn. 6.1 to Eqn. 6.9 in terms of the perturbation quantities and discarding all but linear terms in order to maintain consistency with Eqns. 6.4, 6.5 and 6.6, the following forms of linearised equations of motion are obtained :

$$(X_{\dot{u}} - m)\dot{u} + X_u \Delta u = 0 \qquad \text{Eqn. 6.7}$$

$$(Y_{\dot{v}} - m)\dot{v} + Y_v v + (Y_{\dot{r}} - m x_G)\dot{r} + (Y_r - m u_0) r = 0 \qquad \text{Eqn. 6.8}$$

$$(N_{\dot{v}} - m x_G)\dot{v} + N_v v + (N_{\dot{r}} - I_Z)\dot{r} + (N_r - m x_G u_0) r = 0 \qquad \text{Eqn. 6.9}$$

No consideration has been given in the above treatment to the forces and moments created by rudder deflection. It is usual to assume that the rudder will give rise to a side force and moment which are directing proportional to the rudder angle. Following the addition of the rudder terms, Eqns. 6.7 , 6.8 and 6.9 are more conveniently expressed in a dimensionless form, by dividing them with $1/2\rho u_0^2 L^2$ and $1/2\rho u_0^2 L^3$ respectively. This results in the usual form, the linearised equations of motion used in steering and manoeuvring

$$(Y'_{\dot{v}} - m')\dot{v}' + Y'_v v' + (Y'_{\dot{r}} - m'x'_G)\dot{r}' + (Y'_r - m')r' + Y'_\delta \delta = 0 \qquad \text{Eqn. 6.10}$$

$$(N'_{\dot{v}} - m'x'_G)\dot{v}' + N'_v v' + (N'_{\dot{r}} - I'_Z)\dot{r}' + (N'_r - m'x'_G)r' + N'_\delta \delta = 0 \qquad \text{Eqn. 6.11}$$

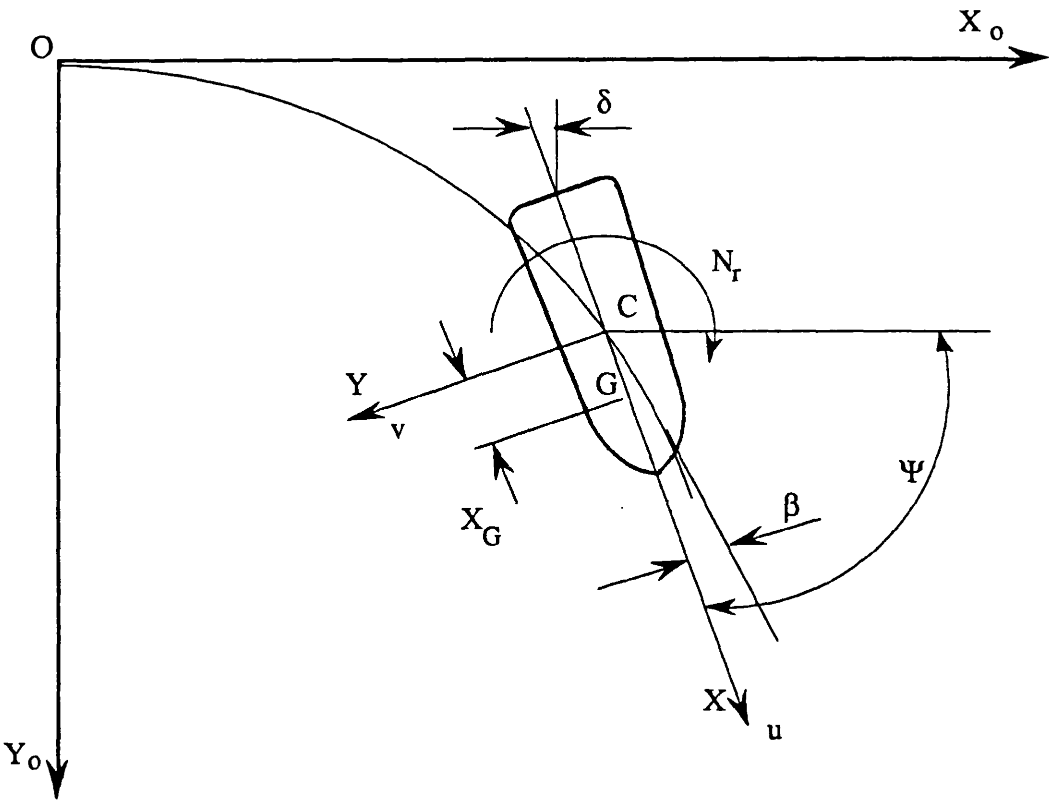
The dimensionless quantities in the above equations are defined in Table 6.1.

Although Eqns. 6.10 and 6.11 expressed the linear equations of motion as pair of simultaneous first order differential equations, where the constant coefficients are dimensionless acceleration and velocity derivatives, it is possible to express these equations in an alternative form. It was first shown by Nomoto [3] that these equations can be written as a pair of decoupled second order equations as follows :

$$T'_1 T'_2 \ddot{r}' + (T'_1 + T'_2)\dot{r} + r' = K'\delta + K'T'_3 \dot{\delta}' \qquad \text{Eqn. 6.12}$$

$$T'_1 T'_2 \ddot{v}' + (T'_1 + T'_2)\dot{v} + v' = K'_v \delta + K'_v T'_4 \dot{\delta}' \qquad \text{Eqn. 6.13}$$

The terms in the above equations, and their algebraic relationships with the acceleration and velocity derivatives are given in Table 6.2.



X hydrodynamic force acting on ship due to surge
Y hydrodynamic force acting on ship due to sway
N hydrodynamic moment acting on ship due to yaw

u longitudinal velocity of ship
v lateral velocity of ship
r yaw rate of ship

δ rudder deflection angle
β drift angle
Ψ heading angle

m mass of ship
X_G distance fwd of amidship from centre of gravity
I_Z moment inertia about amidship

Fig. 6.1 Co-ordinate Axes System Adopted for Mathematical Modelling

It is common practice in the analysis of trial manoeuvers, both at full scale and with free running models, to use a more simple expression than that given in Eqns. 6.12 and 6.13. *Nomoto* first proposed an equation given as follows :

$$T'\dot{r}' + r' = K'\delta \qquad \text{Eqn. 6.14}$$

6.2 MANOEUVRING CRITERIA

6.2.1 Turning Ability

When the turning ability of a ship is mentioned, it is usually described in the context of its turning circle as shown in Fig. 6.2. Measurements of the advance, transfer and diameter are quoted as a means of quantifying the ship's inherent turning stability. However, most ships, whether stable or unstable, turn with a circle diameter between two to three times the length of the ship, so that the terminal turning behaviour is not a useful means of assessing the manoeuvrability of a ship.

Before considering the turning circle, the initial turning ability of the ship will be examined, after the application of the rudder while following a straight course. In this way, the linear equations developed in the previous section may be used, since the deviations from the initial steady state are still small.

A suitable definition of turning ability can be taken as the heading angle turned through from an initial straight course, per unit rudder angle applied, after the ship has travelled one ship length. This situation is shown in Fig. 6.3 where the heading response to a rudder movement of angle δ in a time t'_r, following which the rudder remains constant. The heading response can be obtained by solving the first part of Eqns. 6.12 and 6.13 for this rudder time history, together with zero rate and heading angle initial conditions, as follows :

$$\begin{aligned}\frac{\psi(t)}{\delta} = K'\Big[& t' - (T'_1 + T'_2 - T'_3) + t'_r/2 \\ & + \frac{(T'_1 - T'_3)T'^2_1}{(T'_1 - T'_2)t'_r}(e^{t'_r/T'_1} - 1)e^{-t'/T'_1} \\ & - \frac{(T'_2 - T'_3)T'^2_2}{(T'_1 - T'_2)t'_r}(e^{t'_r/T'_2} - 1)e^{-t'/T'_2}\Big]\end{aligned} \qquad \text{Eqn. 6.15}$$

Table 6.1 The Dimensionless Quantities

v'	$= v / u$	$Y'_{\dot{v}}$	$= Y_{\dot{v}} / 0.5\rho L^3$
r'	$= rL / u$	$Y'_{\dot{r}}$	$= Y_{\dot{r}} / 0.5\rho L^4$
$\dot{v}'$	$= \dot{v}L / u^2$	$N'_{\dot{v}}$	$= N_{\dot{v}} / 0.5\rho L^4$
$\dot{r}'$	$= \dot{r}L^2 / u^2$	$N'_{\dot{r}}$	$= N_{\dot{r}} / 0.5\rho L^5$
t'	$= tu / L$	Y'_v	$= Y_v / 0.5\rho L^2 u$
m'	$= \rho\nabla / 0.5\rho L^3 = 2C_B(B/L)(T/L)$	Y'_r	$= Y_r / 0.5\rho L^3 u$
I'_z	$= \rho\nabla k^2 / 0.5\rho L^5 = 2C_B(B/L)(T/L)(k/L)^2$	N'_v	$= N_v / 0.5\rho L^3 u$
x'_G	$= x_G / L$	N'_r	$= N_r / 0.5\rho L^4 u$
		Y'_δ	$= Y_\delta / 0.5\rho L^2 u^2$
		N'_δ	$= N_\delta / 0.5\rho L^2 u^2$

Table 6.2 Definition of Coefficients K' and T'

$$T'_1 T'_2 = \frac{(Y'_{\dot{v}} - m')(N'_{\dot{r}} - I'_z) - (Y'_{\dot{r}} - m'x'_G)(N'_{\dot{v}} - m'x'_G)}{Y'_v(N'_r - m'x'_G) - N'_v(Y'_r - m')}$$

$$T'_1 + T'_2 = \frac{(Y'_{\dot{v}} - m')(N'_r - m'x'_G) + (N'_{\dot{r}} - I'_z)Y'_v - (Y'_{\dot{r}} - m'x'_G)N'_v - (N'_{\dot{v}} - m'x'_G)(Y'_r - m')}{Y'_v(N'_r - m'x'_G) - N'_v(Y'_r - m')}$$

$$T'_3 = \frac{(N'_{\dot{v}} - m'x'_G)Y'_\delta - (Y'_{\dot{v}} - m')N'_\delta}{N'_v Y'_\delta - Y'_v N'_\delta}$$

$$T'_4 = \frac{(N'_{\dot{r}} - I'_z)Y'_\delta - (Y'_{\dot{r}} - m'x'_G)N'_\delta}{(N'_r - m'x'_G)Y'_\delta - (Y'_r - m')N'_\delta}$$

$$K' = \frac{N'_v Y'_\delta - Y'_v N'_\delta}{Y'_v(N'_r - m'x'_G) - N'_v(Y'_r - m')}$$

$$K'_v = \frac{(N'_r - m'x'_G)Y'_\delta - (Y'_r - m')N'_\delta}{Y'_v(N'_r - m'x'_G) - N'_v(Y'_r - m')}$$

$$T' = T'_1 + T'_2 - T'_3$$

Similarly, by solving Eqns. 6.12 and 6.13 for the same rudder input,

$$\frac{\psi(t)}{\delta} = K'\left[t' - T' + t'_r/2 + -\frac{T'^2}{t'_r}(e^{t'_r/T'} - 1)e^{-t'/T'}\right] \qquad \text{Eqn. 6.16}$$

Study of Eqns. 6.15 and 6.16 confirms that both solutions tend to a similar asymptote if :

$$T' = T'_1 + T'_2 - T'_3 \qquad \text{Eqn. 6.17}$$

If the time for the rudder movement tends to zero, and non-dimensionalised time is set to t = 1, (which is equivalent to moving one ship length), then Eqns. 6.6 and 6.7 become :

$$\frac{\psi(t)}{\delta} = K'\left[1 - (T'_1 + T'_2 - T'_3) + \frac{(T'_1 - T'_3)}{(T'_1 - T'_2)}T'_1 e^{-1/T'_1} - \frac{(T'_2 - T'_3)}{(T'_1 - T'_2)}T'_2 e^{-t'/T'_2}\right]$$

and

$$\frac{\psi(t)}{\delta} = K'\left[\left[1 - T' + T'e^{-1/T'}\right]\right] \qquad \text{Eqn. 6.18}$$

Norrbin [2] first introduced the idea of a turning index and used Eqn. 6.18 to denote what he termed the 'P' number. This is the heading change per unit rudder angle for one ship length travelled, described in terms of the *Nomoto* indices K' and T'. *Norrbin* suggested a tentative value of P > 0.3 for vessels smaller than the tanker. A value of P = 0.3 is equivalent to a 10^{o} heading change in one ship length, when the rudder is placed hard over, in excess of 30^{o}. Equation 6.9 may be expanded into the form

$$P = \frac{\psi(t)}{\delta} = 1/2\,\frac{K'}{T'}\left[1 - \frac{1}{3T'} + \frac{1}{12T'^2} - \frac{1}{60T'^3} + \cdots\cdots\right] \qquad \text{Eqn. 6.19}$$

and when T' is large this reduces to

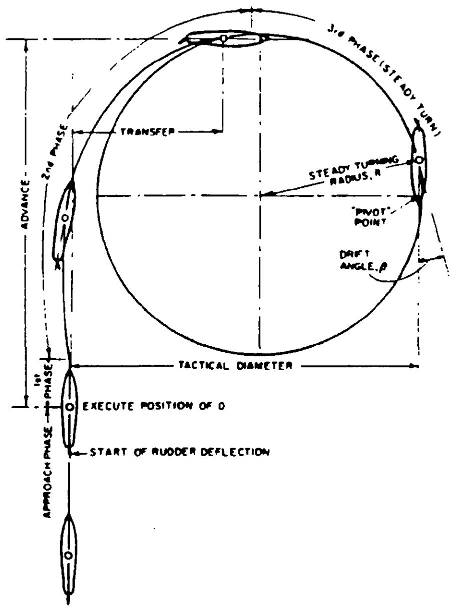


Fig. 6.2 Turning Path of a Ship

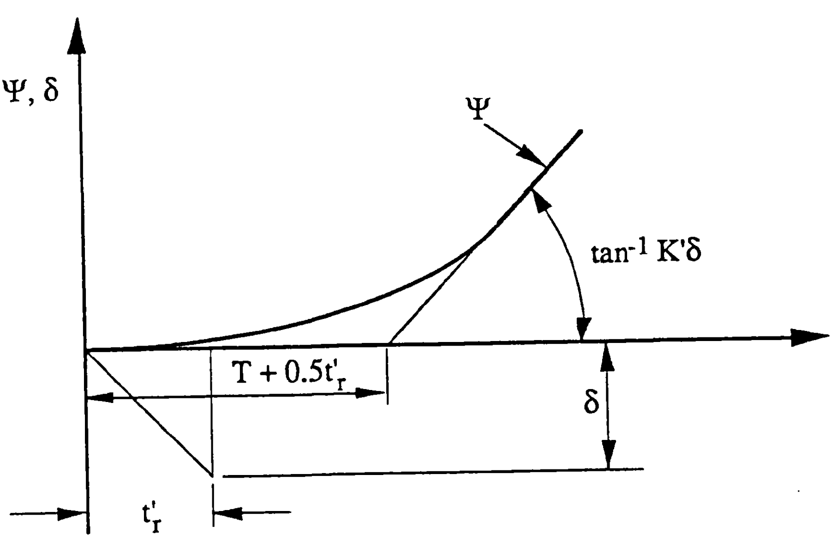


Fig. 6.3 Turning Ability of a Ship

$$P \cong 1/2 \frac{K'}{T'} \qquad \text{Eqn. 6.20}$$

6.2.2 Dynamic Stability

For a linear dynamic system to be stable it is necessary for the roots of the characteristic equations to be negative. In most ship manoeuvring problems, these roots are usually real so that this requirement is satisfied if the time constants are positive. The condition for stability therefore reduces to :

$$Y'_v(N'_r - m'x'_G) - N'_v(Y'_r - m') > 0 \qquad \text{Eqn. 6.21}$$

and may also be expressed as

$$\frac{N'_r - m'x'_G}{Y'_r - m'} > \frac{N'_v}{Y'_v} \qquad \text{Eqn. 6.22}$$

This latter inequality is useful in defining the requirement for dynamic stability. It simply indicates that the centre of pressure in pure yaw should be ahead of the centre pressure in pure sway if the ship is to be dynamically stable.

6.3 ESTIMATION OF DERIVATIVES

At the present time, the most reliable method of determining the numerical values of the velocity and acceleration derivatives is by means of captive model testing, using either a planar motion mechanism or a rotating arm. However, this is an expensive and time consuming process and it would be a great advantage if the derivatives could be established empirically after analysis of experimental results obtained on planar motion and rotating arm devices.

In 1970, *Wagner Smitt* [4] proposed :

$$Y'_v = -5.0\left(\frac{T}{L}\right)^2 = -\pi\left(\frac{T}{L}\right)^2 (1.59) \qquad \text{Eqn. 6.23}$$

$$Y'_r = +1.02\left(\frac{T}{L}\right)^2 = -\pi\left(\frac{T}{L}\right)^2 (-0.32) \qquad \text{Eqn. 6.24}$$

$$N'_v = -1.94\left(\frac{T}{L}\right)^2 = -\pi\left(\frac{T}{L}\right)^2 (0.62) \qquad \text{Eqn. 6.25}$$

$$N'_r = -0.65\left(\frac{T}{L}\right)^2 = -\pi\left(\frac{T}{L}\right)^2 (0.21) \qquad \text{Eqn. 6.26}$$

while *Norrbin* [2] suggested

$$Y'_v = -\pi\left(\frac{T}{L}\right)^2 \left[+1.69 + 0.08\,\frac{C_B\,B}{\pi T}\right] \qquad \text{Eqn. 6.27}$$

$$Y'_r = -\pi\left(\frac{T}{L}\right)^2 \left[-0.645 + 0.38\,\frac{C_B\,B}{\pi T}\right] \qquad \text{Eqn. 6.28}$$

$$N'_v = -\pi\left(\frac{T}{L}\right)^2 \left[+0.64 - 0.04\,\frac{C_B\,B}{\pi T}\right] \qquad \text{Eqn. 6.29}$$

$$N'_r = -\pi\left(\frac{T}{L}\right)^2 \left[+0.47 - 0.18\,\frac{C_B\,B}{\pi T}\right] \qquad \text{Eqn 6.30}$$

and *Inoue* [6] recommended

$$Y'_v = -\pi\left(\frac{T}{L}\right)^2 \left[+1.00 + 1.4\,\frac{C_B\,B}{\pi T}\right] \qquad \text{Eqn. 6.31}$$

$$Y'_r = -\pi\left(\frac{T}{L}\right)^2 \left[\frac{1}{2}\right] \qquad \text{Eqn. 6.32}$$

$$N'_v = -\pi\left(\frac{T}{L}\right)^2 \left[\frac{2.0}{\pi}\right] \qquad \text{Eqn. 6.33}$$

$$N'_r = -\pi\left(\frac{T}{L}\right)^2 \left[\frac{1.04}{\pi} - \frac{4T}{\pi L}\right] \qquad \text{Eqn. 6.34}$$

Examination of these formulae reveals discrepancies in the values obtained for the four velocity derivatives. This is most likely due to variations in the experimental data and regression techniques used.

In an attempt to clarify the situation, *Clarke* [1] performed a multiple regression analysis of all available data. His results are summarised in the following expressions for velocity and acceleration derivatives :

$$\frac{-Y'_v}{\pi\left(\frac{T}{L}\right)^2} = 1 + 0.40 C_B B/T \qquad \text{Eqn. 6.35}$$

$$\frac{-Y'_r}{\pi\left(\frac{T}{L}\right)^2} = -1/2 + 2.2B/L - 0.08B/T \qquad \text{Eqn. 6.36}$$

$$\frac{-N'_v}{\pi\left(\frac{T}{L}\right)^2} = 1/2 + 2.4T/L \qquad \text{Eqn. 6.37}$$

$$\frac{-N'_r}{\pi\left(\frac{T}{L}\right)^2} = 1/4 + 0.039B/T - 0.56B/L \qquad \text{Eqn. 6.38}$$

$$\frac{-Y'_{\dot v}}{\pi\left(\frac{T}{L}\right)^2} = 1 + 0.16 C_B B/T - 5.1(B/L)^2 \qquad \text{Eqn. 6.39}$$

$$\frac{-Y'_{\dot r}}{\pi\left(\frac{T}{L}\right)^2} = 0.67B/L - 0.0033(B/T)^2 \qquad \text{Eqn. 6.40}$$

$$\frac{-N'_{\dot v}}{\pi\left(\frac{T}{L}\right)^2} = 1.1B/L - 0.041B/T \qquad \text{Eqn. 6.41}$$

$$\frac{-N'_{\dot r}}{\pi\left(\frac{T}{L}\right)^2} = 1/12 + 0.017 C_B B/T - 0.33B/L \qquad \text{Eqn. 6.42}$$

6.4 ESTIMATION OF RUDDER AREA

Numerous formulae in determining the rudder area have been given at one time or another by many authors. These normally help the designer in determining the rudder area required, but in most cases the area thus determined is on the low side for offshore supply vessels. The following formulae are quoted here as giving good results and as being the most appropriate ones for offshore supply vessel rudder design.

a. *Norgaa*rd [17] states that a rudder area of 6.3% of the lateral plane area in a moderate size of offshore supply vessel has given good manoeuvring characteristic.

b. *Simpson* [18] gives the minimum percentage of the rudder area to the lateral plane area as approximately equal to 5% and states that this figure would decreased with increasing size.

c. *Taylor* [19] gives the recommended rudder area as equal to 1/25 of the area of the immersed midship area..

d. *Det Norske Veritas* [20] recommended that the minimum rudder area as

$$A_r = \frac{T \text{ x LBP}}{100}\left[1 + 25\left(\frac{B}{LBP}\right)^2\right] \qquad \text{Eqn. 6.43}$$

The above formula applies only to rudder arrangements in which the rudder is located directly behind the propeller. For any other rudder arrangement, DnV requires an increase of at least 30%. Rudder areas used compare well with those measured from the technical press.

6.4.1 Estimation of Rudder Derivatives

The side force Y created by the rudder is calculated on the basis that the rudder acts like a low aspect ratio wing, so that

$$Y = \frac{1}{2}\rho c^2 A C_L \qquad \text{Eqn. 6.44}$$

where c is the water speed past the rudder, A is the rudder area and C_L is the lift coefficient If this side force is non-dimensionalised in the usual manner by the factor $\frac{1}{2}\rho u^2 L^2$ then

$$Y' = \left(\frac{A}{LT}\right)\left(\frac{T}{L}\right)C_L\left(\frac{c}{u}\right)^2 \qquad \text{Eqn. 6.45}$$

from which

$$Y' = \left(\frac{A}{LT}\right)\left(\frac{T}{L}\right)\left(\frac{\partial C_L}{\partial \delta}\right)\left(\frac{c}{u}\right)^2 \qquad \text{Eqn. 6.46}$$

and since the rudder is approximately half the ship length aft of amidships,

$$N'_\delta = -\frac{1}{2}Y'_\delta \qquad \text{Eqn. 6.47}$$

Although the lift curve slope of the rudder $\partial C_L / \partial \delta$ and the velocity ratio $(c/u)^2$ are variables which are different for every ship, their product has been assumed constant throughout this studies.

6.5 ESTIMATION OF TURNING DIAMETER

While the turning circle does not give a complete measure of the ship's manoeuvring performance, it has the advantage of having practical use to the ship's officers, is often important as a contractual requirement to the ship builder, and can be checked by measurement during trials.

In conformity with general practice, the turning circle characteristics discussed here have been non-dimensionalised using ship length The terms used and the geometry of the circles are all defined in Fig 6.3. In this study, the regression equations developed by *Lyster* and *Knights* [9] are used to estimate the steady turning diameter, tactical diameter, advance, transfer and the steady speed in the turn for any rudder angle. Following are the required equations for twin screw vessels :

$$\frac{STD}{L} = 0.727 - 197\frac{C_B}{|\delta|} + 4.65\frac{B}{L} + 41.0\frac{Trim}{L} + 188\frac{1}{\delta}$$

$$-218\frac{SpCh}{LT}(NR - 1) + 3.20\frac{V_A}{\sqrt{L}} + 25.56\frac{A_B}{LT} \qquad \text{Eqn. 6.48}$$

$$\frac{TD}{L} = 0.140 + 1.0\frac{STD}{L} \qquad \text{Eqn. 6.49}$$

$$\frac{Ad}{L} = 1.10 + 0.514\frac{TD}{L} \qquad \text{Eqn. 6.50}$$

$$\frac{Tr}{L} = -0.357 + 0.531\frac{TD}{L} \qquad \text{Eqn. 6.51}$$

$$\frac{V_T}{V_A} = 0.543 + 0.028\frac{TD}{L} \qquad \text{Eqn. 6.52}$$

where

NR = number of rudders
A_B = submerged bow profile area
V_A = velocity of approach
V_T = velocity on steady turn
Sp = span of rudder
Ch = chord of rudder

6.6 DESCRIPTION OF THE COMPUTER MODEL

A manoeuvring performance prediction tool for offshore supply vessels was created incorporating suitably adaptations of currently accepted practice. The resulting tool allows the user to determine the required size of rudder for a given vessel in order to provide adequate manoeuvring performance such as dynamic stability and the characteristics of the turning circle. The program in common with all computer programs may be broken down into a number of easily understood algorithms as shown in Fig. 6.4.

The program requires only the following input values :

a. ship parameters L, B, T and C_B

b. initial ship speed

c. centre of gravity of vessel

d. depth of water

e. number of screws

f. radius of gyration of vessel

The program will calculate the velocity and acceleration derivatives and also evaluate the minimum rudder area according to *Det Norske Veritas Rule* [20] so that the rudder derivatives can be estimated. The program will proceed to evaluate the time constants and later check whether the vessel in question is stable or not (as defined by Eqn. 6.22).

From here, the user will have two choices, either to proceed with the unstable vessel or change the rudder area until a stable vessel is obtained and proceed to estimate the turning circle diameter.

A sample output of the computer program is given in Table 6.3.

6.7 CONCLUSION

In this study, a design tool is developed that enables a designer to explore the effects on the manoeuvring characteristics of a ship at an early stage of the design spiral. The designer will only need basic information of the ship form to run the computer program. This will help the designer to produce relevant data that will ultimately become necessary for regulatory bodies.

Against the background that there is no accepted method of describing and quantifying what is meant by the manoeuvrability of ships, this study has attempted to examine the consequences of simple criteria for manoeuvrability. However, it must be stressed that the method outlined in this study are based on linear equations of motion and are only valid for small departures from a steady course. It is well known that the correct mathematical modelling of ship manoeuvring behaviour requires complex non-linear equations. However, increasing the number of terms in the equations requires that many more coefficients will be needed to create a model for a particular ship. Defining these coefficients empirically at an early stage of a ship design is virtually impossible at present, without recourse to model testing.

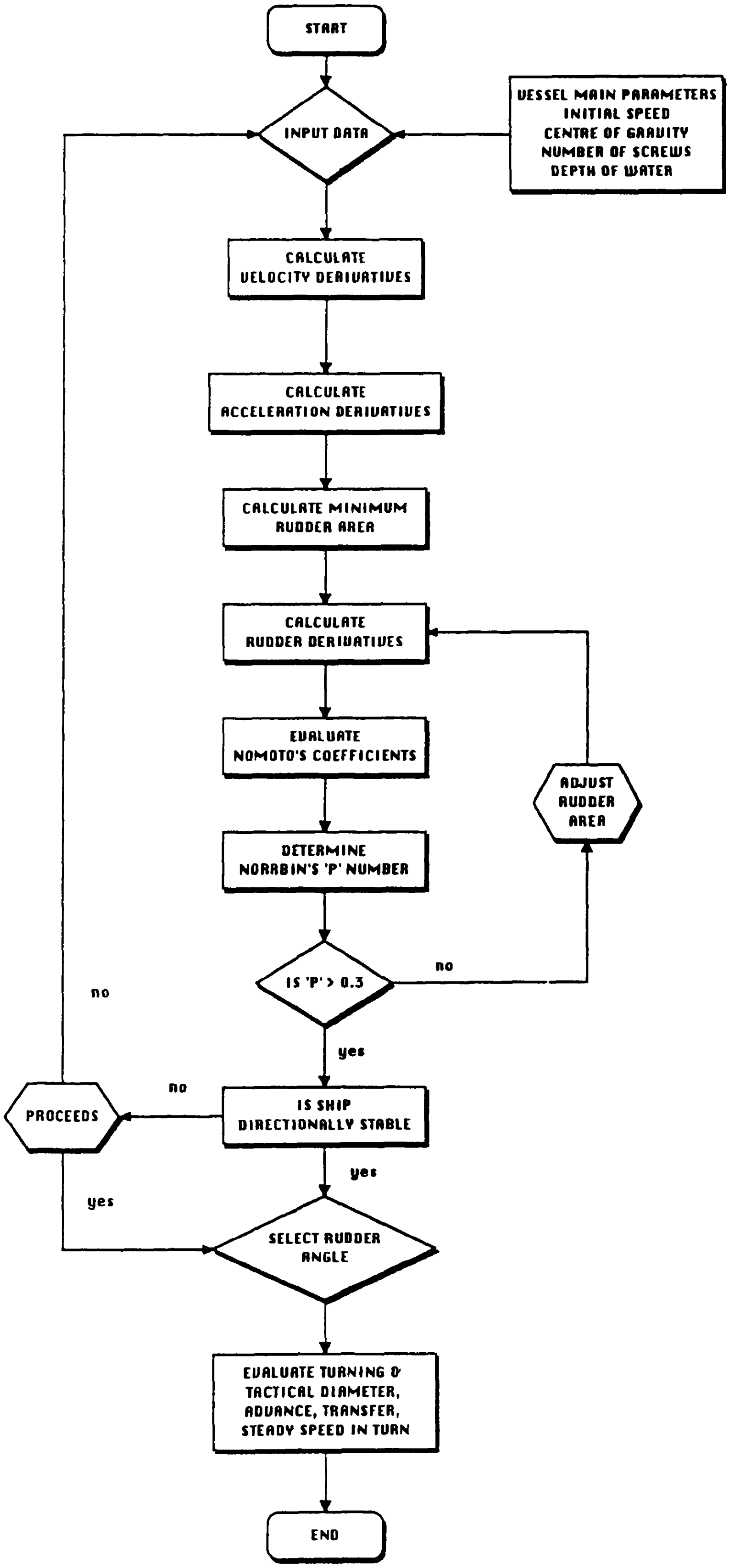


Fig. 6.4 Computer Flowchart of the Manoeuvring Characteristics

INPUT VERIFICATION :

LENGTH (m)	=	54.00
BEAM (m)	=	12.00
MEAN DRAFT (m)	=	4.20
BLOCK COEFFICIENT	=	0.68
CENTRE OF GRAVITY (m from midship)	=	0.037
INITIAL VESSEL SPEED (knot)	=	12.20
RADIUS OF GYRATION (m)	=	0.25 x L
WATER DEPTH TO VESSEL DRAUGHT RATIO (m)	=	1000.0
NUMBER OF PROPELLERS	=	2

LINEAR MANOEUVRING DERIVATIVES

NONDIMENSIONAL MASS	M PRIME	=	0.02293
NONDIMENSIONAL MASS MOMENT	I SUB ZZ	=	0.00143
SWAY VELOCITY DERIVATIVE	Y SUB V	=	-0.03378
SWAY ACCELERATION DERIVATIVE	Y SUB V DOT	=	-0.02013
YAW VELOCITY DERIVATIVE	N SUB V	=	-0.01305
YAW ACCELERATION DERIVATIVE	N SUB V DOT	=	-0.00242
SWAY VELOCITY DERIVATIVE	Y SUB R	=	0.00456
SWAY ACCELERATION DERIVATIVE	Y SUB R DOT	=	-0.00232
YAW VELOCITY DERIVATIVE	N SUB R	=	-0.00450
YAW ACCELERATION DERIVATIVE	N SUB R DOT	=	-0.00082
SWAY RUDDER DERIVATIVE	Y SUB DELTA	=	0.00527
YAW RUDDER DERIVATIVE	N SUB DELTA	=	-0.00263

TIME CONSTANTS AND GAINS FOR NOMOTO'S EQUATION

DOMINANT SHIP TIME CONSTANT	T1 PRIME	=	3.85727
SHIP TIME CONSTANT	T2 PRIME	=	0.38040
NUMERATOR TIME CONSTANT	T3 PRIME	=	0.82829
NUMERATOR TIME CONSTANT	T4 PRIME	=	0.27031
1ST ORDER EQN. TIME CONSTANT	T PRIME	=	3.40937
RUDDER GAIN FACTOR	K PRIME	=	2.67267
RUDDER GAIN FACTOR	K SUB V PRIME	=	1.29812
RUDDER AREA (m^2)	ARUD	=	5.12000

EVALUATION OF TURNING ABILITY AND STABILITY

CLARKE'S TURNING INDEX	P	=	0.39196
LINEAR DYN. STAB. CRITERION	C	=	-0.09506

COMMENTARY : *VESSEL IS NOT COURSE STABLE*

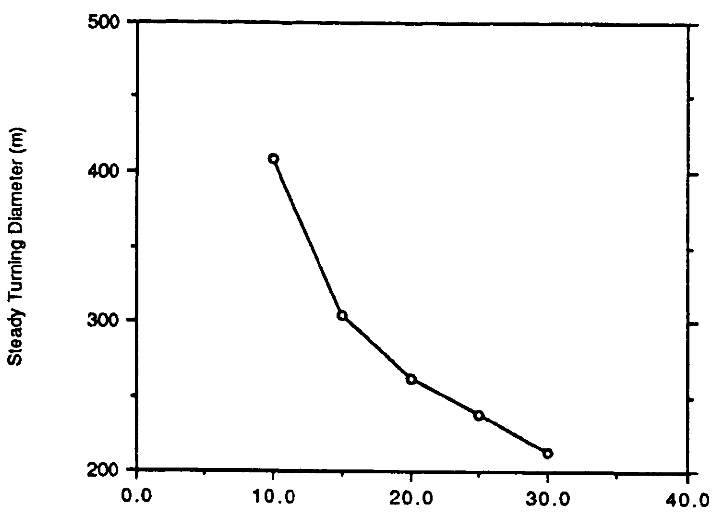


Fig. 6.5 Effects of Rudder Deflection on Steady Turning Diameter

Table 6.3 Sample Output From the Computer Program

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CHAPTER 7

ESTIMATION OF COSTS

7.0 INTRODUCTION

Shipbuilding cost (or price) estimates are needed by people in a great variety of positions and for many reasons. Here is a partial list that illustrates the range of uses :

a. Fleet managers need costs estimates for purposes of choosing between alternative investment opportunities, establishing budgets or predicting charter and insurance rates,

b. Naval architects need cost estimates for preliminary design purposes. These encompass both feasibility studies of alternative technologies and optimisation studies aimed at finding the best combination of major design parameters. Cost estimates are also useful in making detailed design decisions and in selecting equipment,

c. Shipyard managers need cost estimates for bidding on new construction, for deciding whether to make or buy certain items of equipment and for negotiating prices for extras or credits applied to shipbuilding contracts.

The shipbuilding cost estimation process may be broadly divided into three main categories :

a. feasibility study cost estimation (preliminary or budget estimation),
b. design study cost estimation (detail investigation), and
c. fully detailed cost estimation.

The feasibility study costs estimation is what this thesis is concerned about. It is aimed at nothing more than first approximations which can be obtained fairly quickly, but which are nevertheless associated to some extent with the physical features of the vessels under consideration. The second phase is undertaken at a stage when smaller number of alternatives, which are very close to the optimum design are compared while the third phase is carried out at tendering level, when sufficient technical and economic data will be available for the proposed design.

According to Gilman [7], focus for considering approaches to ships' costs and also to some of the linkages between costs and some major issues in the maritime industries can be viewed as the chart given in Fig. 7.1. The chart has a central axis which follows the order of one of the common procedures by which daily costs at sea and in port are calculated. There are four different prices mentioned: a newbuilding price; a newbuilding estimate based on preliminary design studies and shipyard costs and used in parametric costs studies; a second-hand price; and finally a charter rate. The first three of these have to be intepreted in the context of the financial and economic factors which modify their impact and these are specified in the second level which deals with the conversion of prices to capital costs and also with bringing them to a daily basis. Following this the chart refers to the main elements in operating costs, namely, insurance, maintenance, crew and fuel. In certain standard costing practices, fuel is classified as a voyage cost rather than an operating cost. However, in this chart, it is included in operating costs because the emphasis here is on producing daily costs in port and at sea; and to limiting this to those costs which are a direct function of ship size and speed and can, therefore, be used in parametric studies.

The chart then moves on to other voyage costs which includes port costs, starting with sea access and moving on to a certain component of cargo handling costs and port dues. It also includes agency fees, which are a proportion of freight revenues, and those damage costs which are a particular function of the route. The final section of the chart deals with network costs where reference is made to inland distribution patterns; the costs of inland modes; return of empty containers and trailers; inventory costs of cargo; and the frequency requirements of a particular service.

7.1 METHODS OF ESTIMATING SHIPBUILDING COSTS

There are various methods of ship capital costs estimation and nearly all these methods seem to be based either on the ship's functional capability (such as deadmass) or on its technical characteristics (such as the masses of various components).

7.1.1 Estimating On a Basis of Functional Capability

Some fleet managers discuss ship capital costs in terms of so many pound sterling per deadmass tonne. A report from the Australian Bureau of Transport Economics [8] uses a shipbuilding cost estimating method that appears to be typical of those employed by

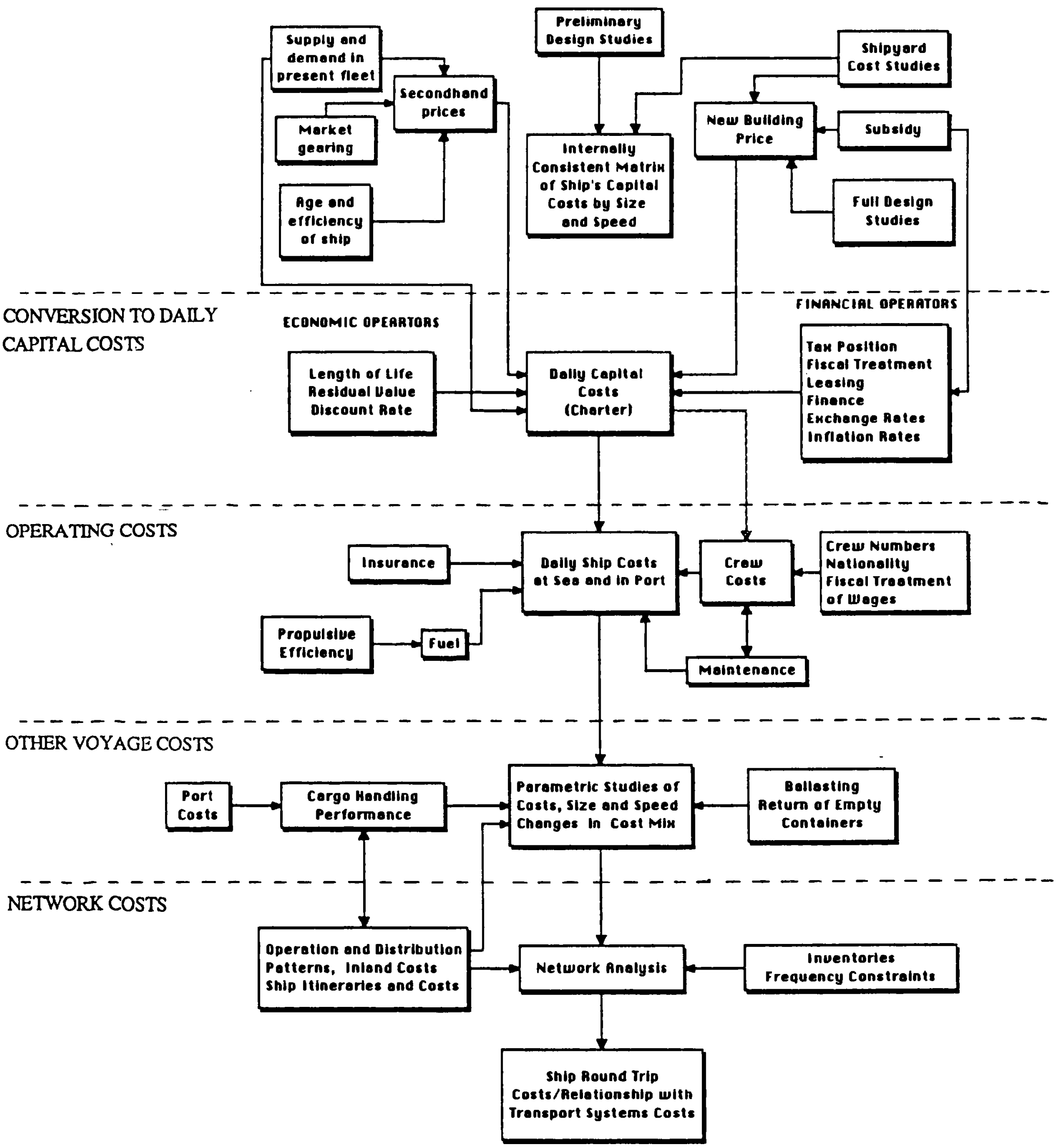

Fig. 7.1 Scheme for a Review of Ships' Costs [7]

shipping economists, but goes a step beyond the simple £ per deadmass method, that is

$$P = C(dwt)^B \times F \qquad \text{Eqn 7.1}$$

where

P	=	ship capital costs in millions of Australian dollars
C	=	a coefficient unique to each type of ship
dwt	=	deadmass in thousands of tonnes
B	=	an exponent unique to each type of ship, and
F	=	a stochastic error term (taken to equal to one in the reference)

To give an idea of spread of values, C ranged in the report from 1.45 for container ships to 3.14 for ro/ro's; while B ranged from 0.60 for bulk carriers to 0.85 for container ships.

7.1.2 Estimating On a Basis of Technical Characteristics

The number of bases for cost estimates can range all the way from a single measure such as the ship's lightmass to hundreds of measures in terms of masses, power, areas, and so forth, all applied to groups of related items entering into the construction of the ship. These latter costs can also be broken down between material and labour components.

7.1.2.1 Lightship as a Basis

In a study done some years ago [2], it was found that costs of ships, hydrofoil craft, cushion vehicles and aircraft all tended to fall into straight lines when plotted on log paper with lightship as the independent variable. This led to the following general expression :

$$P = C(W_E)^{0.87} \qquad \text{Eqn. 7.2}$$

where

P = cumulative average costs for each number of identical units appropriate to the kind of variable
C = an approximate coefficient, the value of which is a function of relative complexity of vehicle
W_E = lightship

Relative values of C varied from a baseline of unity for simple cargo ships to 24 for 400-knot aircraft.

7.1.2.2 Hull size and Power as a Basis

In a well known study carried out by economists at Northwestern University, USA [9], ship capital costs were estimated on a dual basis. Hull costs were derived from cubic number (which is the product of ship's length, beam and depth divided by 100), while the machinery costs were derived from the shaft power :

$$P = 668(CN) + 29600(P_S)^{0.5} \qquad \text{Eqn. 7.3}$$

where

P = ship capital costs in US dollars (1950)
CN = cubic number (in cubic feet/100)
P_S = shaft power at normal cruising speed

Eide [10], a Norwegian economist, uses a more elaborate approach but one still applicable in the earliest stages of design. Though his study is devoted to tankers, his methods have wider application. He divides the ship into hull, machinery and equipment components. He first estimates the steel mass and then proceeds to estimate costs for each component as follows :

$$\text{Cost of hull} = h_0 + h_1 p_s W_s + h_2 p_w W_s^a \qquad \text{Eqn. 7.4}$$

where

p_s = price per tonne of steel
p_w = price per hour of labour
W_s = steel mass in tonnes
h_0, h_1 and h_2 are positive constants and a is less than 1.

$$\text{Cost of machinery} = m_1(P_S)^b + m_2 p_w (P_S)^c \qquad \text{Eqn. 7.5}$$

where

m_1, m_2, b and c are positive constants and P_S is shaft power

$$\begin{aligned}\text{Cost of equipment} = {} & e_1 p_w N_t^d (dwt)^f + e_2 (dwt)^g \\ & + e_3 p_w (lbd)^h + e_4 (lbd)^i \\ & + e_5 p_w (lbd)^j + e_6 (lbd)^k \end{aligned} \qquad \text{Eqn. 7.6}$$

where

dwt = deadmass
N_t = number of tanks separated by bulkheads
lbd = product of ship's length, beam, and depth.

On the right hand side of the equation , the first pair of terms is for the cargo equipment, the second pair for accommodation equipment, and the third pair for other equipment. This method can lead to fairly accurate predictions if only one can acquire returned costs of outfitting broken down in the manner shown.

7.1.2.3 Simple Mass Breakdown as a Basis

An inherent part of the preliminary design calls for estimating the three major components of the ship's lightmass, that is, steel mass, outfit mass and machinery mass. These same components often serve the preliminary designer in his cost estimations. At this stage, too, the designer will usually go a step further in sophistication and make separate estimates of the costs of material, labour and overhead. Material and labour will be estimated for each of the three categories of mass while overhead will be taken as an overall figure.

Breaking the ship down into such major physical components allows a great increase in estimating accuracy since appropriate costs coefficients can be individually applied. Obviously, the material costs per tonne of structural steel will be much less than the costs per tonne of outfitting components. Whereas costs for other components are based on masses, material and labour, costs for machinery are usually based on installed power.

This method of cost estimation will be applied extensively in this study. Previous researches [5], [6] found that it produced reliable capital costs. The method was published by Carryette [3] and adjusted for 1991 money values.

7.2 LABOUR COSTS

Manhours are the basis of all direct labour costs, and once estimated, it is only necessary to apply wage rates, overheads and profit to arrive at the total labour costs. The total labour costs can be subdivided into :

a. steel labour manhours and costs,
b. outfit labour manhours and costs, and
c. machinery labour manhours and costs.

In this study, the method adopted is that developed by Carreyette [3] in 1978 and the costs are estimated at early 1991 level in pounds sterling and reflect the costs of shipbuilding in an average United Kingdom shipyard.

7.2.1 Steel Labour Manhours and Costs

The steel labour manhours from a variety of sources was related to the steel mass by the following relationship

$$K = R_h C_B (W_S / LBP)^{1/3} \qquad \text{Eqn. 7.7}$$

where R_h is the actual labour manhours per tonne of steel.

K is constant for a shipyard but would vary between shipyards. Carreyette uses a value of K of 227, which he feels is high because of the mixed nature of type of ships, and gives a value of K equals 180 for any shipyard building one or two types of ships. Using K as 227 and rearranging the previous equation gives

$$\text{Steel labour manhours} = R_h W_S$$

$$= 227 W_S^{2/3} L^{1/3} / C_B \qquad \text{Eqn. 7.8}$$

To convert the steelwork labour manhours to total steelwork labour costs, it is necessary to apply an average wage rate (reflecting both skilled and unskilled trades), overheads and profit. The 1991 average shipbuilding wage rate was £6.05/hour. This can be conveniently updated by using current wage rates published by Eurostat [11]. Fig. 7.2 shows the average hourly rate in shipbuilding industry since 1982, from £3.1/hr in 1982 to £6.05/hr in 1991, which is approximately a two fold increase in ten years.

Overhead costs (sometimes called establishment charges) are costs which cannot be allocated to any particular contract, such as supervisory staff, training, power supplies, capital charges on plant, insurance, local taxes, maintenance, research and development, and marketing. Overheads are often expressed as a percentage of total direct labour costs typically between 60% to 150%.

In a shipyard, it is the job of the management and not the cost estimator to decide on an appropriate profit margin to add to the estimated building costs. The decision will be influenced by the experience of the yard with the type of work in question (and the associated uncertainty of the costs estimate), the yard's order book, the state of the shipbuilding market and competition, and the standing of the customer. A figure of about 10% of estimated costs is aimed at, but not always achieved in the present competitive world of shipbuilding.

$$\text{Steel Labour Costs} = £\frac{A_1 W_S^{2/3} L^{1/3}}{C_B} \qquad \text{Eqn. 7.9}$$

where A_1 is a constant which includes the wage rate, overhead, profit margin and the value of K. If K is 227, overheads are 100% and profit margins are 10% then

$$A_1 = 6.05 \times 227 \times 2.0 \times 1.10$$
$$= 3021$$

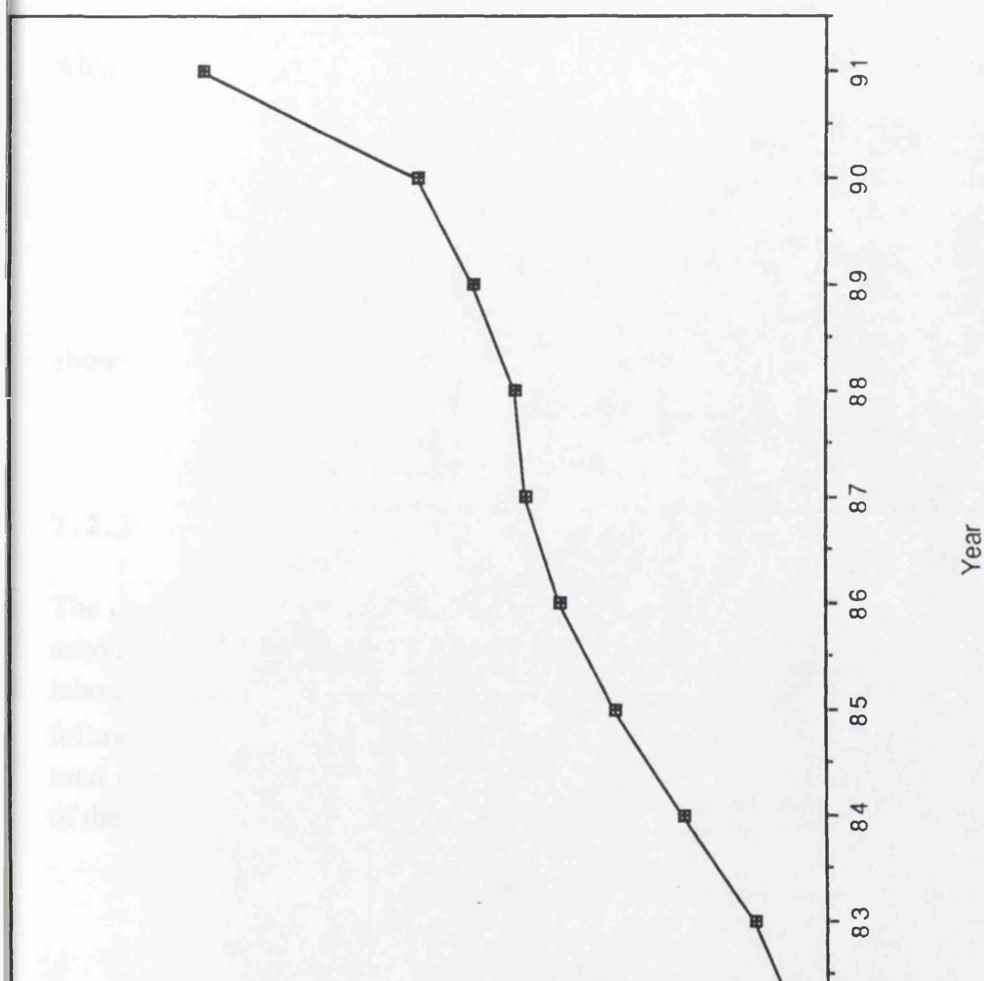

Fig. 7.2 Average Hourly Earnings in Shipbuilding (United Kingdom)

The value of A_1 can be given by the following equation for different wage rates and overheads for K of 227 and profit margin of 10%

$$A_1 = WR \times (437.5 + 62.5 \times (0.04 \times OVH - 3.0)) \qquad \text{Eqn. 7.10}$$

where

WR = average hourly wage rates in £/hr

OVH= overheads expressed as a percentage

The values of A_1 are plotted against various wage rates for various overheads is shown in Fig. 7.3.

7.2.2 Outfit Labour Costs

The outfit labour manhours are difficult to validate since the shipyards vary in their accounting practices. For example, one shipyard may put the subcontracted items as labour costs and others as material costs. Carreyette found that outfit labour costs followed the same pattern as the steel labour costs, that is, $H = \alpha x^n$ where H is the total manhours, x is the size or quantity, α is a constant and $n \leq 1$. The general form of the equation is given by

$$\text{Outfittng Labour Costs} = £C_1 W_O^{2/3} \qquad \text{Eqn. 7.11}$$

where C_1 is a factor which includes the level of productivity, wage rates, overheads and profit.

The value of C_1 and its variation with overheads and wage rates for a profit margin of 10% can be obtained from the equation below and illustrated in Fig. 7.4.

$$C_1 = WR \times (30.0 \times OVH + 2937.5) + 50.0 \qquad \text{Eqn. 7.12}$$

where wage rate for 1991 is £6.05/hr and can be updated easily.

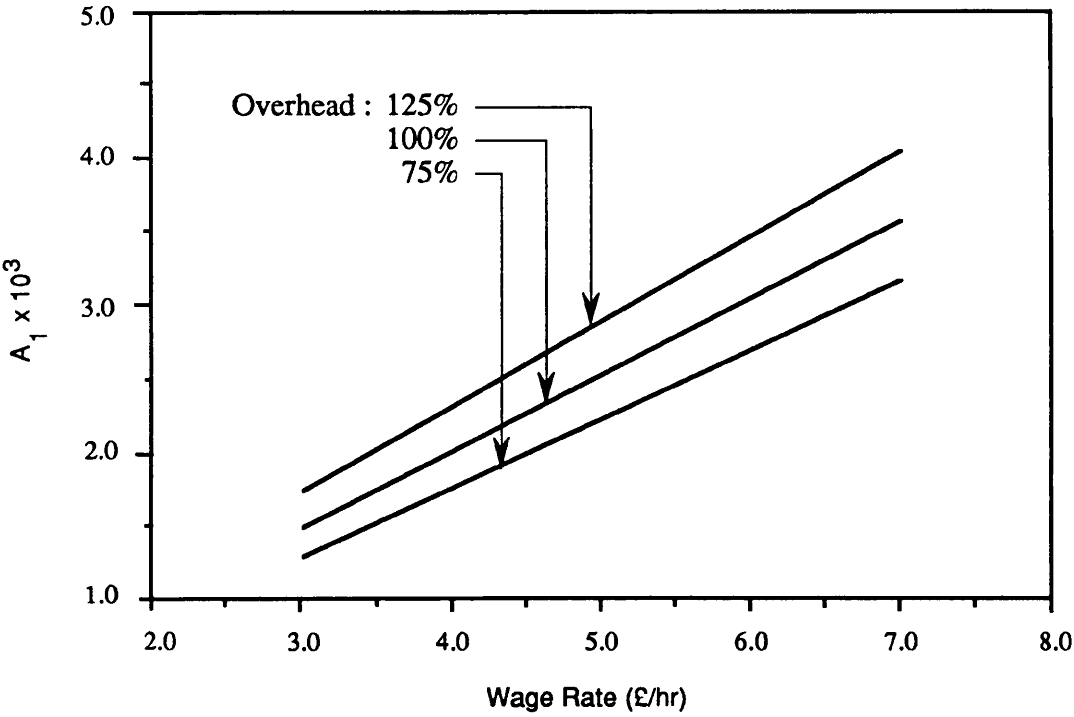

Fig. 7.3 Steel Labour Cost Constant for Various Values of Wage Rates and Overheads (profit margin 10%)

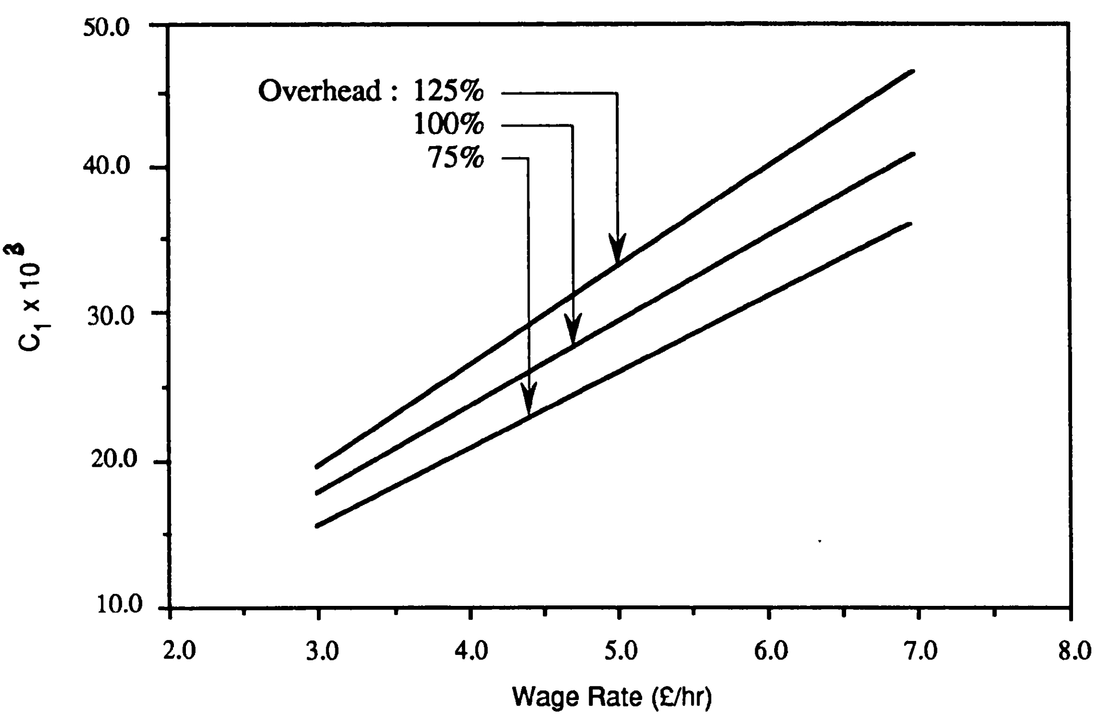

Fig. 7.4 Outfit Labour Cost Constant for Various Values of Wage Rates and Overheads (profit margin 10%)

7.2.3 Machinery Labour Costs

The recorded manhours for machinery installation suffers from the same drawbacks as the outfit labour manhours, that is, since most of the work is subcontracted, it is recorded as 'material costs'. Therefore the machinery costs is calculated directly from the equation

$$\text{Machinery Labour Costs} = £F_1 \times P_B^{0.82} \qquad \text{Eqn. 7.13}$$

where P_B is the total installed power.

The value of F_1 and its variation with overhead and wage rates for a profit margin of 10% can be estimated from the equation below and illustrated in Fig. 7.5.

$$F_1 = WR \times (OVH \times 1.125 + 117.92) \qquad \text{Eqn. 7.14}$$

7.3 MATERIAL COSTS

As for labour costs, the material costs are also subdivided into three conventional groups, that is, steel material costs, outfitting material costs and machinery material costs. The material costs indices for shipbuilding material and equipment is difficult to obtain but it is taken that structural steel wholesale price indices were an acceptable guideline and is shown in Fig. 7.6. Although open to criticism it validated well in Table 7.2.

Carreyette found that material costs showed similar characteristics as those obtained for the labour costs. Thus the general form of equation is given by

$$\text{Material Costs} = \alpha x^n \qquad \text{with } x = \text{mass of material} \qquad \text{Eqn. 7.15}$$

Furthermore, the material cost functions did not show the same degree of economy of scale in size or quantity increases as the labour costs functions. For steel labour costs, steel mass has an index of 0.667 compared to 1.0 for steel material costs. for outfitting labour costs, outfit mass has an index of 0.667 compared to 0.95 for outfitting material costs, while for machinery labour costs and material costs, the installed power has the same index of 0.82.

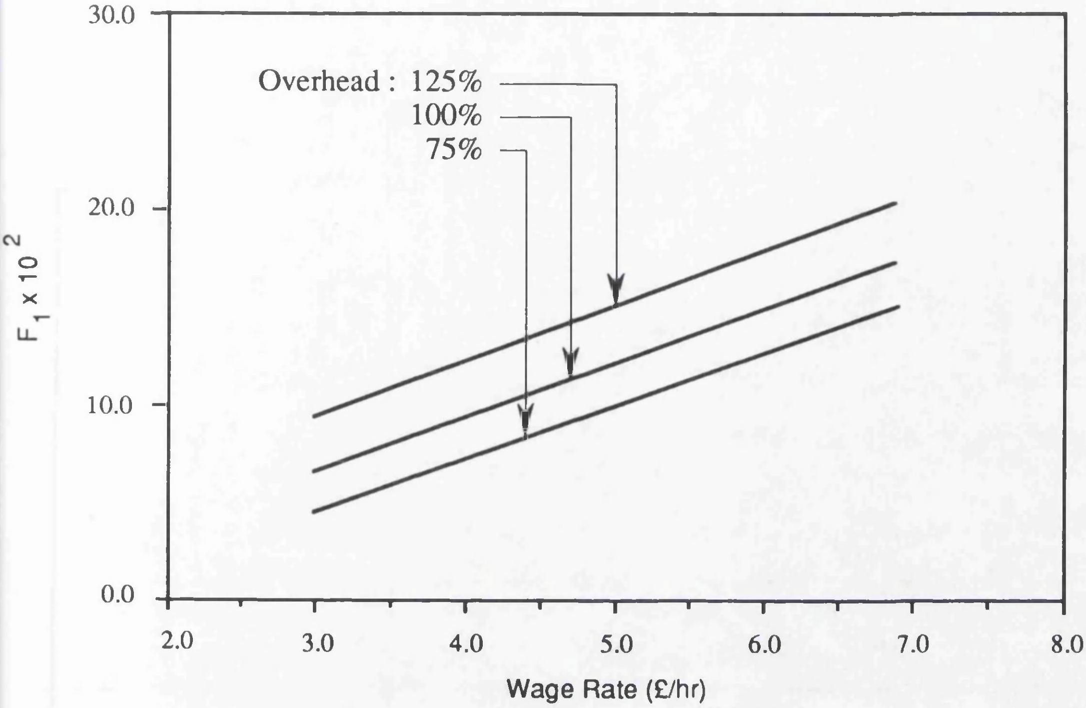

Fig. 7.5 Machinery Labour Cost Constant for Various Values of Wage Rates and Overheads (profit margin 10%)

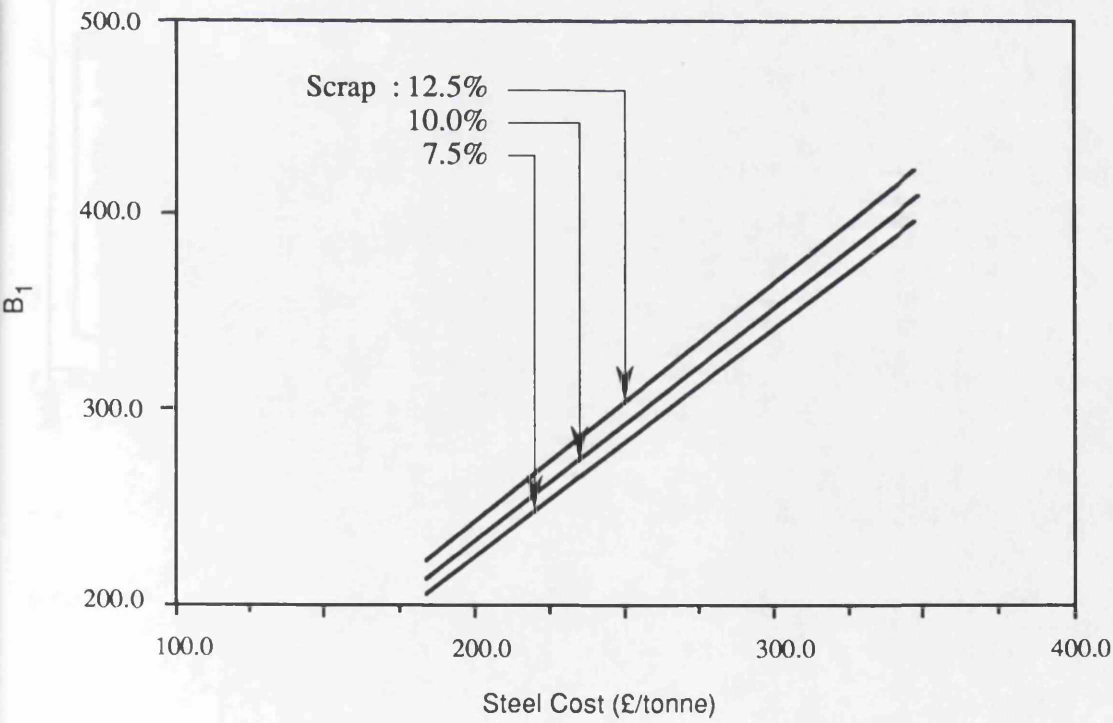

Fig. 7.7 Steel Material Cost Constant for Various Values of Steel Costs and Wastage (profit margin 10%)

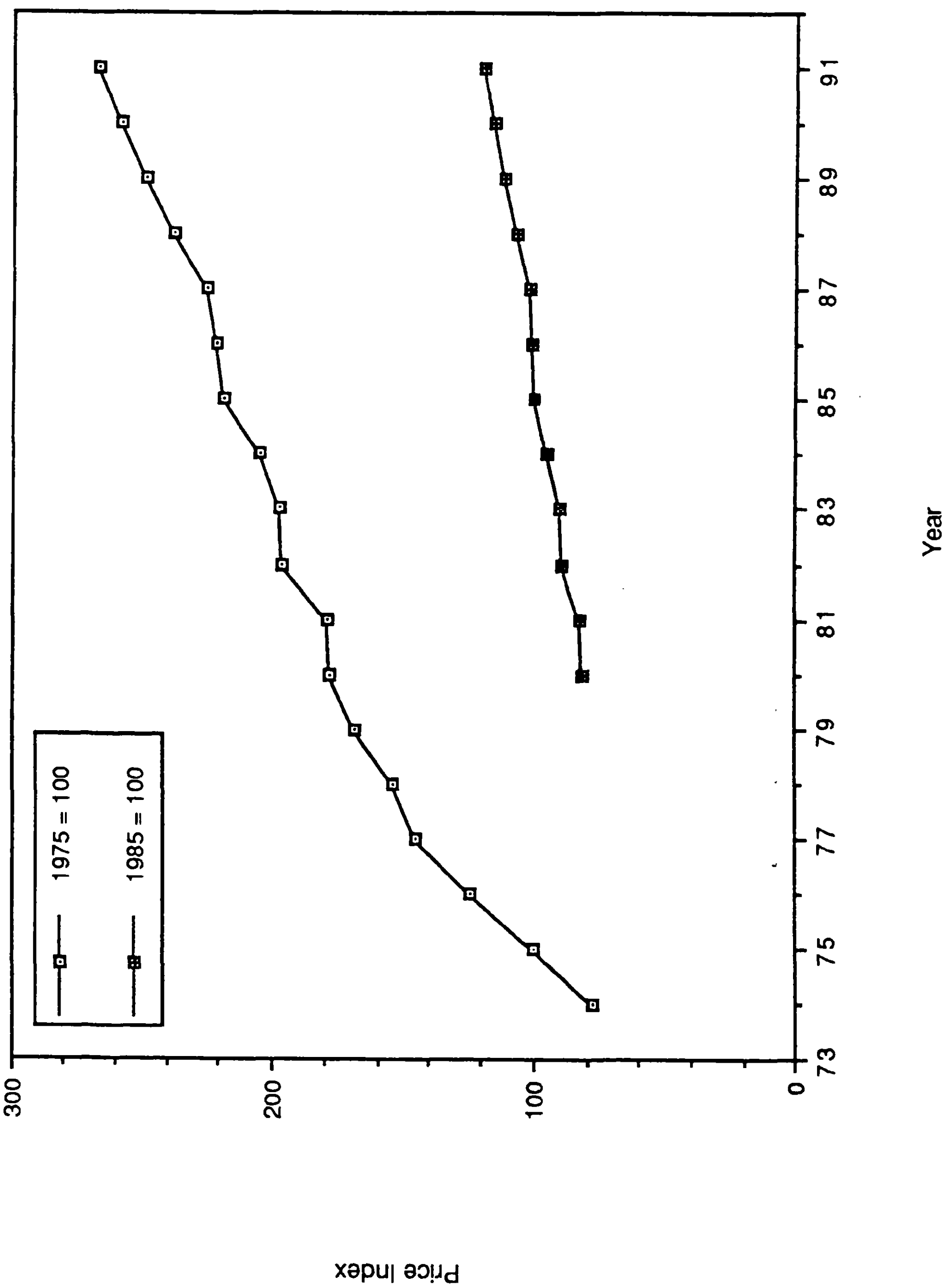

Fig. 7.6 Structural Steel Wholesale Price Index

7.3.1 Steel Material Costs

The steel material costs is given by the equation

$$\text{Steel Material Costs} = £\, B_1 \times W_S \qquad \text{Eqn. 7.16}$$

where B_1 is a constant reflecting the cost of steel per tonne and the scrap percentage. The values of B_1 for various cost of steel per tonne and scrap percentage are shown in Fig. 7.7. For a fixed value of steel material costs, increase in scrap percentage increases the value of B_1. Thus B_1 can be estimated from the following equation

$$B_1 = \text{STLCOS} \times 1.18 \times ((\text{SCRAP} - 7.5)/100.0 + 1.0) + 0.20 \qquad \text{Eqn. 7.17}$$

where SCRAP is the scrap percentage or wastage of material, and is calculated from the following 4th order polynomial of C_{b1} [11].

$$\text{SCRAP} = S(1) + S(2) \times C_{b1} + S(3) \times C_{b1}^2 + S(4) \times C_{b1}^3 + S(5) \times C_{b1}^4 \ \% \qquad \text{Eqn. 7.18}$$

where C_{b1} is the block coefficient at 0.80 depth of the vessel and is estimated from

$$C_{b1} = C_B + (1 - C_B)(0.80 \times D - T)/3T \qquad \text{Eqn. 7.19}$$

7.3.2 Outfit Material Costs

Outfit material costs are calculated from the following equation

$$\text{Outfit Material Costs} = £\, D_1 \times W_O^{0.95} \qquad \text{Eqn. 7.20}$$

where D_1 is a constant reflecting the equipment costs of the manufacturer.

The values of D_1 since 1975 is shown in Fig. 7.8 and the formula for evaluating D_1 is given by

$$D_1 = 1500 \times \text{material index}/100 \qquad \text{Eqn. 7.21}$$

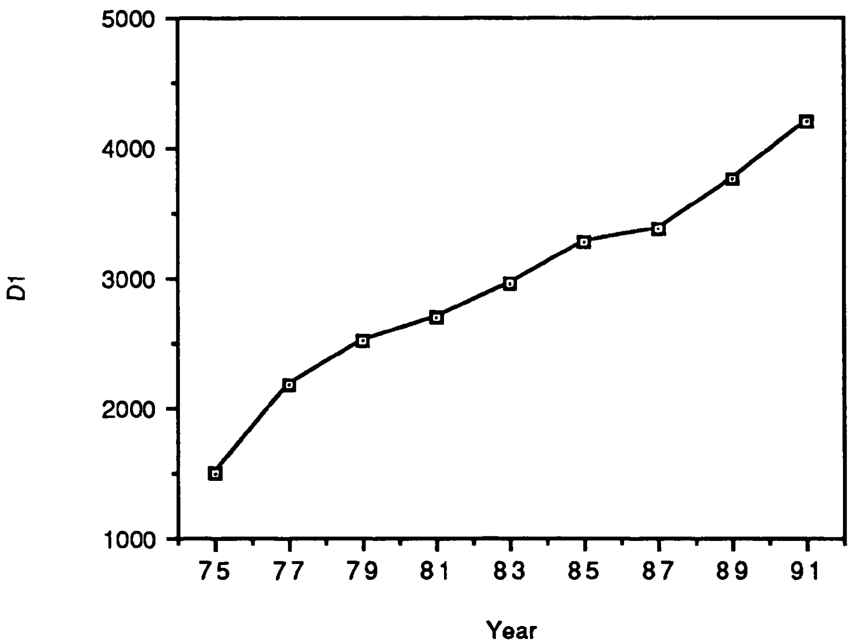

Fig. 7.8 Outfit Material Cost Constant (profit margin 10%)

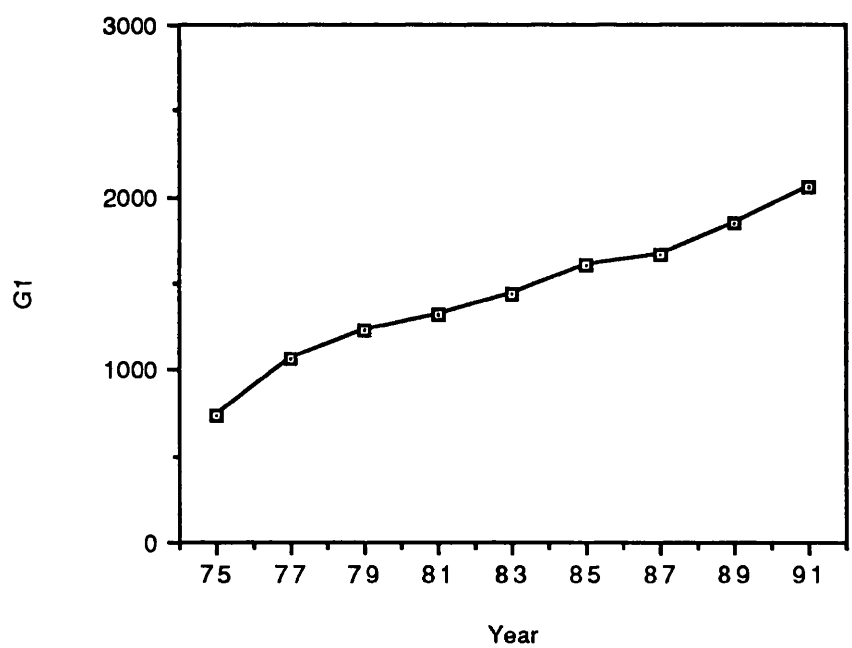

Fig. 7.9 Machinery Material Cost Constant (profit margin 10%)

1975 was taken as the base year and the value of material index of that year is taken as 100. The values of D_1 given by Carreyette are compared with those calculated by the above equation and shown in Table 7.1. Since outfit material costs indices were not available, shipbuilding structural cost price index is used. as Table 7.1 shows it gives fairly good results for the limited values that were available.

7.3.3 Machinery Material Costs

Economic studies comparing alternative machinery are common. In general, each different type of machinery has different first costs, both of the basic prime mover, and installed as a complete system. Machinery material costs considered in this study are assumed for vessels with diesel installations (since this is the most common type in practice). The costs are calculated from the following equation

$$\text{Machinery Costs} = G_1 \times (P_B)^{0.82} \qquad \text{Eqn. 7.22}$$

The values of G_1 since 1975 is shown in Fig. 7.9 where the formula for evaluating G_1 is given by

$$G_1 = 735 \times \text{material index}/100 \qquad \text{Eqn. 7.23}$$

with the values of material index as steel material index. The values of G_1 calculated by the above equation are shown in Table 7.1 and are found to be in good agreement with the limited data available.

7.4 MISCELLANEOUS ITEM

Having produced an approximate method for early costing, it is necessary to consider what special equipment or facilities are to be included in the costs. Such features related to offshore supply vessels are grades of steel used in the hull, whether propellers are fixed or controllable pitch, the inclusion of stern and bow thrusters, stabilizers, or heavy cargo handling gear, and to the type of propulsion machinery. Each of these becomes important in itself as the design progresses, and in the preliminary stage, we ought to know the degree of cost changes associated with them.

Table 7.1 Comparative Values for D_1 and G_1 and Updated Values

Year	D_1		G_1	
	Given	Calculated	Given	Calculated
6/75	1500	1500	735	735
6/76	1725	1724	845	845
6/77	2011	1989	980	975
1/78		2110		1034
1/79		2369		1161
1/80		2531		1240
1/85		3277		1606
1/90		4005		1962
1/91		4200		2058

7.4.1 Steel Grades

The use of higher tensile steel can be allowed for by upgrading the value of B_1 in the equation for steel material costs. The following mix of steel grades are assumed in the calculation of steel material costs ; 75% to 85% of Grade A, remainder Grades D, E, AH, DH or EH as given by Carreyette.

7.4.2 Shafts and Propellers

The equation for machinery costs applies to single screw vessels with fixed pitch propellers. As most of the offshore supply vessels are equipped with twin screws, the machinery costs have to be increased by 15%.

As modern offshore supply vessels have controllable pitch propellers, the costs of such items must be included separately since the costs of such propellers are from two to three times those of fixed pitch propellers having the same thrust. Therefore, a costs addition must be made to the machinery material costs and this is given (for one propeller) approximately by

$$\delta C_p = £12800\, Q_o^{1/2} \qquad \text{Eqn. 7.24}$$

where

Q_o = overall torque equivalent to 0.79 P_B/N tonne-metre with N as rpm of propeller.

7.4.3 Thrusters

Almost all offshore supply vessels are equipped with bow and stern thrusters as one of the functions of such vessel is to maintain station in open unprotected seas or in close proximity to offshore platforms. Equation on material costs does not include the costs of these thrusters, and if required, the additional costs for a thruster steelwork inway, power source, controls and installation amounts approximately to

$$C_T = £\,29091 + 85.42T_T \qquad \text{Eqn. 7.25}$$

where

C_T = costs at early 1991 rates
T_T = power in Kilowatts

7.5 TOTAL CAPITAL COSTS

The total capital costs for offshore supply vessels is given by

Capital Costs = Steel Labour Costs + Outfit Labour Costs + Machinery Labour Costs + Steel Material Costs + Outfit Material Costs + Machinery Material Costs + Miscellaneous Costs

$$= £\frac{A_1 \times W_S^{2/3} L^{1/3}}{C_b} + B_1 W_S + C_1 W_O^{2/3} + D_1 W_O^{0.95}$$

$$+ F_1.P_B^{0.82} + G_1.P_B^{0.82} + \text{Misc. Costs} \qquad \text{Eqn. 7.26}$$

A 10% profit margin is included in the features A_1, B_1, C_1, D_1, F_1 and G_1. However, the profit margin (PROFIT in percentage) can be adjusted by the following equation

$$\text{Capital Costs} = £\ \text{Eqn. 7.26} \times ((100 + \text{profit})/110) \qquad \text{Eqn. 7.27}$$

Other factors such as overhead (as percentage), labour wage rate/hr, steel costs £/tonne and material indices for a particular shipyard and year can be adjusted without any difficulty.

Costs derived from this study are meant to indicate how much money a shipyard will have to pay for shipyard labour and materials and overhead as well as making some fixed profit. However, price is influenced by various factors such as market conditions, competition, number of vessels on order of the same type, interest rates, loan cost and availability, subsidies and numerous other factors. So to validate the costs given by this study, published prices of ships are not necessarily a good guide.

The capital costs of a ship were validated with data obtained from a shipyard in Glasgow [13] and is shown in Table 7.2.

7.6 OPERATING COSTS

The estimation of operating costs is a difficult area to rationalise. The operating costs vary for ship types, flag of vessel, age of vessel, operating pattern, trade route, and even identical vessels belonging to the same owner can have different operating costs. The operating costs presented in this study were built up from equations developed from previous offshore supply vessel studies and validated with some actual operating

Table 7.2 Costs Calculated by the Method Described Compared With an Actual Cost

Main Parameters of Vessel	Value
Overall Length (m)	68.7
Breadth (m)	17.5
Depth (m)	7.3
Block Coefficient	0.72
Power (kW)	2 x 2500
Displacement (t)	4748
Cost Item	**£ Sterling**
Steel Labour Costs	1658232
Outfit Labour Costs	1009713
Machinery Labour Costs	904889
Steel Material Costs	341449
Outfit Material Costs	1297304
Machinery Material Costs	2613746
Extra Costs for Twin Screws	527795
Extra Costs for C.P. Propellers	65994
Thrusters Costs (2 x 800 hp)	160000
Output of Program	8579122
Actual Cost of Ship	8782000
Percentage Difference	2.31

As in developing other cost models such as the capital cost, the operating costs must reflect the correct magnitude of the differences in costs between alternatives as much as the absolute values. However, different accounting procedures and subdivisions makes it difficult to compare costs of two shipping companies. In general, the operating costs are usually subdivided as given in Fig. 7.10. Thus, to estimate the annual operating costs, it is subdivided into daily running costs which forms a part of the fixed costs, and variable costs which comprises voyage costs.

The daily running costs are estimated from manning costs, insurance, repair and maintenance costs, stores and supplies costs, victualling and provisions costs, and miscellaneous costs while the voyage costs are estimated from fuel costs and port charges.

7.6.1 Daily Running Costs

The level of daily running costs of any vessels is important. The crew cost element is the most significant cost item in this category. Excluding it and assuming a standard level of operating efficiency, the magnitude of these costs will vary very little between similar ships of any flag engaged in similar trades. The typical subdivision of the daily running costs of an offshore supply vessel operating in the North Sea region is given in Fig. 7.11.

7.6.1.1 Crew Costs

One of the principle components of the operating cost is the crew costs which forms about 20% of the total operating costs. One way of reducing this costs is to reduce manning. However, the manning scale for offshore supply vessels is controlled by strict government regulations. The department of trade [1] recommends that no oil rig supply vessel should be put to sea in the ordinary course of its employment unless it has a crew of not less than :

a. Master
b. Mate
c. Chief engineer
d. Second engineer
e. Three seaman
f. Cook

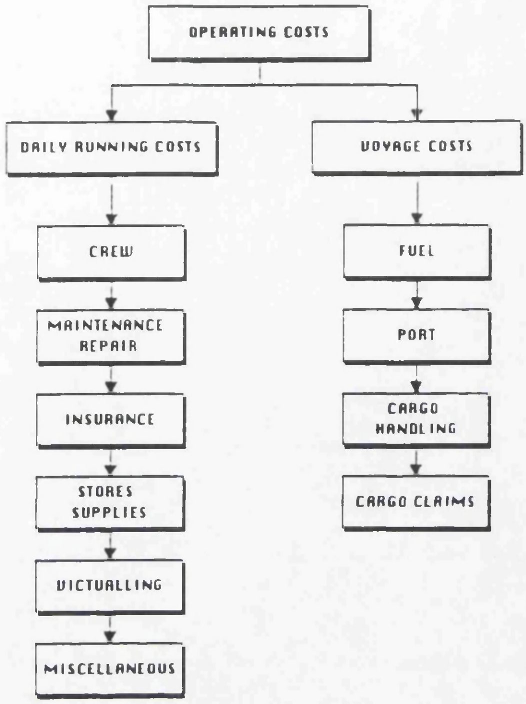

Fig. 7.10 Elements of Operating Costs

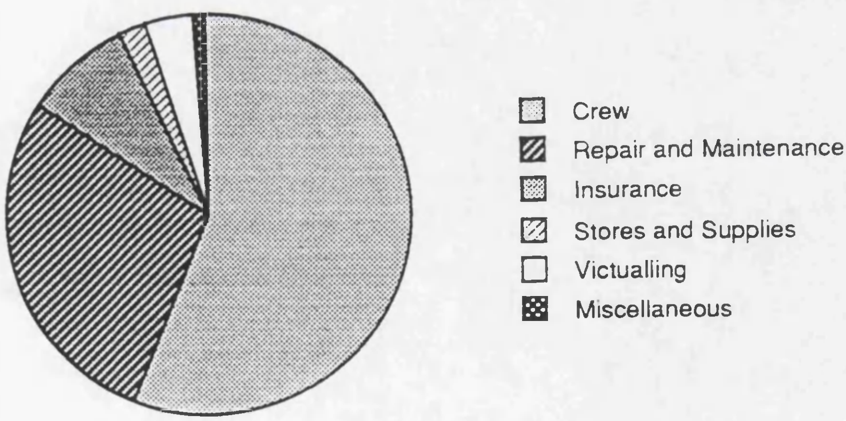

Fig. 7.11 Breakdown of Daily Running Costs for Offshore Supply Vessels Operating in North Sea

Also, where the vessel is employed in supply duties when the crew are responsible for the transfer of considerable quantities of cargo, necessitating extended periods on duty, the basic crew of eight should be augmented by a second mate and a seaman, which would bring the total crew up to ten.

Where the vessel is employed in towing and anchor handling duties, the basic crew of eight should be augmented by the addition of a second mate, third engineer and two seamen, which would bring the total crew up to twelve. Table 7.3 shows various offshore supply vessels operating in the North Sea and the number of crew attached to each vessel.

The different elements of crew costs vary with the flag of operation and are primarily dictated by the conditions of employment agreed between the local or international unions of seafarers (or seamen) and the shipowner or his national association. In general, most agreements comprise of the following factors :

a. basic wages
b. overtime payment
c. supplementary payments - efficient service and certificate pay
d. leave pay and compensation for extra hours and holidays worked
e. medical expenses and sick leave pay
f. training and maintenance allowance and study leave pay
g. personal and national insurance contributions
h. pensions, and
i. travelling and repatriation expenses.

Most owners are under constant pressure to maintain a certain level of wages. The principal pressure emanates from the annual, round of wage demands from well organised national unions seeking to maintain or improve the relative position of their membership in the domestic economy. In the developed countries of North America, North Europe, Scandinavia and Japan which represents the highest crew expenses, the incentive is high to reduce these costs. Owners from such countries usually seek to reduce their crew costs by whatever methods available ranging from reducing their crew number, changing the crew nationality (employing lower cost foreign seaman) to 'flagging-out'. Table 7.4 shows the basic wage of an able seaman in some representative countries in 1987 [35].

However, when examining comparative table of wages, it is essential to check what items have been included and under what conditions the seafarer is employed. For example, an AB (Seaman 1) in one country may be on a basic wage of US$700 per month based on a working week of 40 hours and 120 days vacation per annum, while another may be on US$800 per month based on a working week of 45 hours and 30 days vacation per annum. In a comparative table of basic wages, the former may appear the cheaper while the reverse is true to the owner.

A further complication in international comparison of seafarer's wages concerns exchange rate. A national currency which is strong against the US dollar will indicate higher wages to seafarers and costs to owners than when that currency weakens.

In 1980, a Swedish company estimated that, for each rank, based on basic wage index of 100. The total costs to the owner are given in Table 7.5. However, such a method can only be suitably applied to large vessels with oceangoing trades. The crew costs used in this study are provided by a United Kingdom Shipowner [20], which reflects the average wage scales for the offshore supply vessel industry in the United Kingdom for 1991. The wage scale is given in Table 7.6. Each vessel has two crews working on the basis of one month on, one month off. To allow for other items such as sickness and training, this means that more than two persons must be employed for each position and the normal practice is a ratio of 2.2 : 1.

7.6.1.2 *Marine Insurance Costs*

The vessel herself will be covered by hull and machinery insurance placed in the insurance market with a premium based on value, operating area and past experience. The cargo will be separately insured. Membership of a Protection and Indemnity Club is usually essential to cover an owner against unforeseeable risks.

Hull and Machinery Insurance Costs

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 such insurance costs are expressed as a fraction of the price of the vessel [24], [25], [30] or as a function of the machinery acquisition cost [26], [27]. The hull and machinery costs in this study is expressed as a function of the price of the vessel as given below.

$$\text{Hull and Machinery Insurance Costs} = £0.4 \times \text{capital cost}/100 \qquad \text{Eqn. 7.28}$$

Table 7.3 Number of Crew Attached to Vessels

Name of Vessel	Type of Vessel	Number of Crew
Northern Frontier	AH/Tug/Supply	13
Maersk Clipper	AH/Tug/Supply	16
Stad Sailor	AH/Tug/Supply	13
Seaforth Minara	AH/Tug/Supply	13
Star Polaris	AH/Tug/Supply	12
Seaforth Sovereign	Supply	12
Seaforth Viscount	Supply	12
Stad Scandia	Supply	11
Star Capella	Supply	18
Stirling Elf	Supply	9

Table 7.4 Monthly Basic Wage for an Able Seaman [35]

Country	AB's Basic Wage (*US* $ per month)
Liberia (a)	821
Liberia (b)	739
Greece	439
United Kingdom	650
Norway	912
Japan	1270
United States	1488

* (a) ITF Worldwide Rate
  (b) ITF Far East Rate

Table 7.5 Basic Wage Index

Item	Index
Basic Wage	100.0
Paid Vacation	125.0
Social Security, etc.	75.0
Overtime	1.0
Medical, Illness	4.0
Training	2.0
Welfare	0.5
Travel (days lost)	4.0
Travel (fares, hotel, etc.)	27.0
Miscellaneous	0.5
Total	339.0

* Note : Total cost to owner = 3.4 x basic wage for each rank

Table 7.6 Basic Wage Per Annum for Pure Supply and AH/Tug/Supply Vessels Operating in United Kingdom

Rank	Number of Personnel		Rates In Pound Sterling
	Pure Supply	AH/Tug/Supply	
Master	1	1	25500
Mate	1	1	19500
2nd Mate	-	1	17500
Chief Engineer	1	1	23000
2nd Engineer	1	1	19500
3rd Engineer	-	1	17500
Seaman	3	5	14000
Cook	1	1	14500

Protection and Indemnity Insurance Costs

Protection and indemnity insurance protects the shipowner against special liabilities. Such insurance costs varies considerably from ship to ship and depends on the size of the ship (Gross Register Tonnage (GRT)), shipowner's loss record, whether or not cargo is included, amount deductible and size of the ship's complement. Past studies have expressed such insurance costs as a function of building costs of the ship [27] or GRT [24], [26] or number of crew or perhaps capital charges[29]. In this study, the protection and indemnity insurance cost is calculated on the basis of GRT and is expressed as

Protection and Indemnity Insurance Costs = £3.0 x GRT   Eqn. 7.29

7.6.1.3 Maintenance and Repair Costs

Maintenance and repair costs usually consist of the costs associated with dry docking of the vessel, maintenance of the engines, the main systems, costs associated with other preventive maintenance, repair to damages, costs of inventory related to spares as well as equipment and tools.

The maintenance and repair costs are subdivided into hull and outfit maintenance and machinery maintenance. Machinery maintenance is usually subdivided according to the type of engines. However, as most offshore supply vessels have diesel engines, only such engine maintenance and repair costs are estimated in this study.

Hull and Outfit Maintenance and Repair Costs

The hull and outfit maintenance and repair costs comprise mainly the drydocking costs of the ship. Past ship design studies have revealed that such costs as a function of the cubic number of the ship [30], [31], [32] and similar approach is taken in this study.

Hull and Outfit M & R Costs = £645 (LBD/100)2/3 per year   Eqn. 7.30

Machinery Maintenance and Repair Costs

Machinery maintenance and repair costs forms a substantial part of the total maintenance and repair costs particularly for diesel machinery plant. This cost is usually expressed as a function of the brake power [5], [31], [32] and a similar approach is adopted in this study.

Machinery M & R Costs = £13.30 x P_B per year Eqn. 7.31

7.6.1.4 *Stores and Supplies Costs*

This category includes such items as paint, cleaning materials and cabin stores. It may also includes deck stores such as mooring lines. Such costs are usually taken as a function of the crew number [5], [25], [30]. In this study, such costs are updated from [25] and are given by

Stores and Supplies Costs = £ 6160.0 x number of crew Eqn. 7.32

7.6.1.5 *Victualling Costs*

Such costs includes food and drink, and are usually expressed as a function of crew number. In this study, the victualling costs are obtained from [20] and given by

Victualling Costs = £2190.0 x number of crew Eqn. 7.33

7.6.1.6 *Miscellaneous Costs*

Miscellaneous costs include the costs to cover crew recruitment, communications, standby, medical and shore backup directly linked with manning, sundries and administration. This cost is either taken as a fixed cost [25] or is made as a function of the cubic number of the ship [5], [28]. Here, such cost is taken as

Miscellaneous Costs = £ C x 365 Eqn. 7.34

where C is updated from [5], [25] and is 190.0 for 1991.

7.6.2 Voyage Costs

Voyage costs are largely composed of fuel expenses which vary for a particular vessel with the number of days spent in port and at sea, with sailing speed and conditions, and with location at which fuel is purchased. The voyage costs of offshore supply vessels depend on the style of operation which may be time charter or voyage charter and the amount and type of cargo each voyage. Most supply vessel operations serve one rig, but may serve a number of rigs during each voyage.

Sailing of such vessels are controlled by active elements of demand as indicated in Fig. 7.12. According to the characteristics of the supplies, the sailing of offshore supply vessels can be identified as scheduled voyages and unscheduled voyages. Scheduled voyages are those which are initiated by the requirements of casing, cement, water and equipment initiated by the drilling programme. Spare deadmass may be used to build up reserve stocks if the rig can receive them. Unscheduled voyages are those mostly initiated by random equipment failure. Extra demand for mud, due to loss of circulation or increase in pressure during drilling also creates an unscheduled voyage.

The importance of fuel cost as a major component in the operating costs is considered in this section together with a discussion of some alternative solutions to optimise it.

7.6.2.1 Fuel Economy

Oil price today is much less than forecast before the major oil fall in price in 1986, yet it is still greater than before the first oil price rise of 1973 allowing for inflation. Consequently the fuel charge remains an expensive item in ship operation. The charterer may pay the fuel bill but the owner of vessel without a competitive value of tonnes of fuel per day may not gain a charter with other items being approximately equal. Fuel economy depends on the following factors:

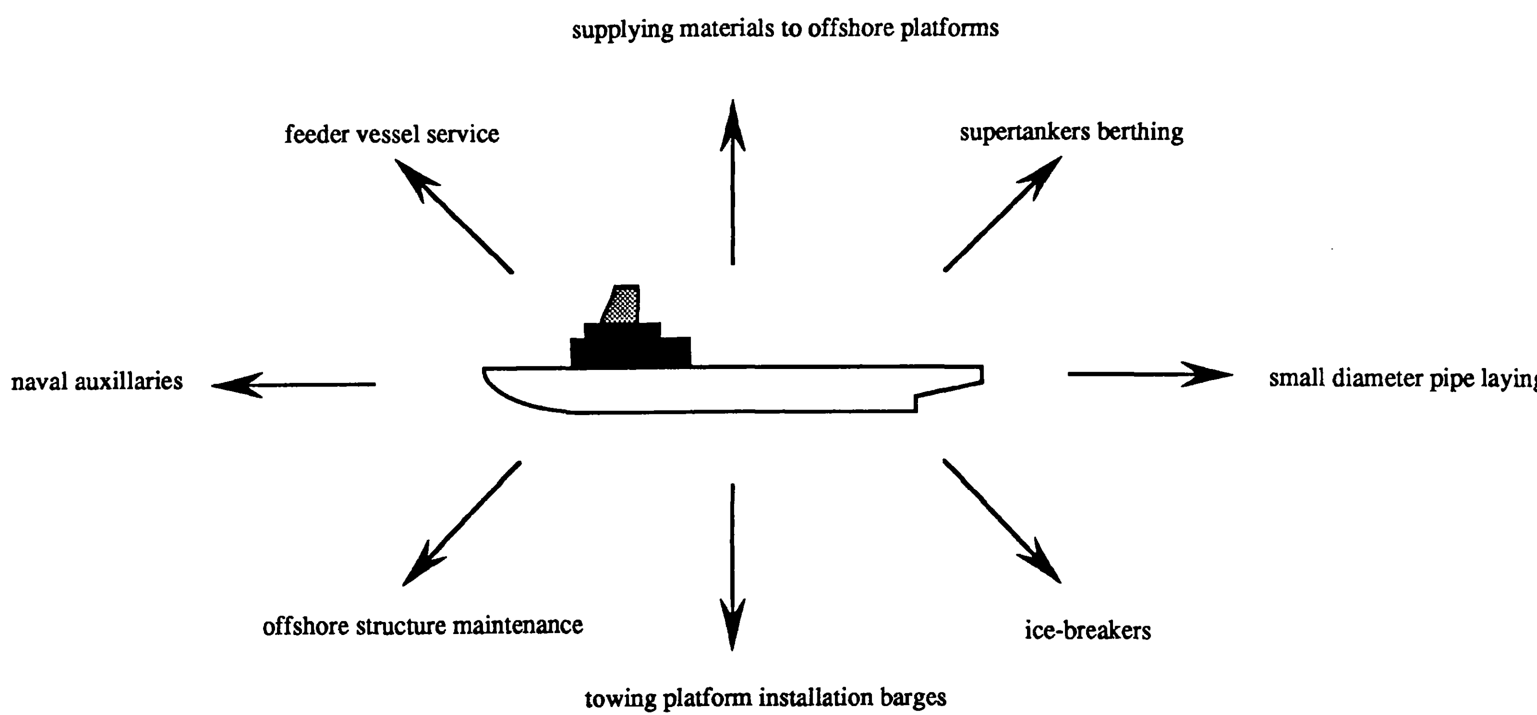

Fig. 7.12 Active Elements of Demand for Offshore Supply Vessels

(a) Speed of Vessel

To increase speed is to increase fuel consumed as power is related to the cube of speed. Supply vessels normally have the power to run at rather high Froude numbers when using their full power and this is also expensive in fuel consumptions. However there may be some scope for varying speed depending on the urgency of the voyage. Design decisions may offer returning to port on only one prime mover even if four prime movers are needed for full speed and this better use of the installed power can reduce fuel consumption.

(b) Quality of Fuel

Heavy fuel oil is generally cheaper than diesel oil and is the usual choice in spite of the fuel treatment plant required on board for its successful use. It is good if all shipbourne prime movers burn the same fuel but is is not always possible, while the actual calorific value of the fuel will effect consumption for a required power.

(c) Specific Fuel Consumption

A reduction in tonnes per day consumption, provided other features are acceptable, can command extra payment in charter hire. Buxton [3] stated that one hour saving could gained $93 per day in charter hire.

(d) Propulsive Efficiency

A good match is required between the prime mover, the gearbox and the propeller to achieve good propulsive efficiency. Compromising is likely to be essential to obtain reasonable performance at reasonable cost over the range of speeds and duties that offshore supply and anchor handling/tug/supply vessels must accept.

(e) Maintenance of Hull and Propellers

It is accepted that ships especially in tropical water can benefit in efficiency of propulsion from regular polishing of their propeller blades and their hull to retain good surface smoothness. The condition of supply supply vessel operations in the North Sea are perhaps special and records of the rate of marine growth in the harbours used could be needed before coming to a conclusion.

7.6.2.1 *Fuel Costs Analysis*

The fuel costs were subdivided into heavy fuel oil costs, marine diesel oil costs and lubricating oil costs. Some cost estimations include lubricating oil in engine room stores and not in fuel oil category. Given that most of it will be used when the engine is running and is not associated with the passage of time, it has been decided in this study that it should be part of the fuel oil category. Typical fuel consumption of offshore supply vessels operating in the North Sea is shown in Fig. 7.13. Two generators of 500 kW each were assumed to be used at sea and in port for generating electricity, running the ventilation plant etc.

(a) Heavy fuel oil consumed at sea/day in tonnes

$$= 204 \times 0.90 \times P_B \times 1.10 \times 24/10^6 \qquad \text{Eqn. 7.35}$$

where 204 gm/kWhr is the typical specific fuel consumption for such vessels, 0.90 is a factor to convert the installed power to normal continuous rating, 1.10 is the 10% reserve fuel.

(b) Diesel oil consumed at sea/day in tonnes

$$= 204 \times \text{AUXKW} \times \frac{0.50}{0.95} \times 24 / 10^6 \qquad \text{Eqn. 7.36}$$

where the engine operates at 50% of the maximum continuous rating at sea at an efficiency of 95%.

(c) Cylinder and system luboil consumption at sea/day in tonnes

$$= 0.50 \text{ gm/kWhr} \times P_B \times 0.90 \times 24/10^6 \qquad \text{Eqn. 7.37}$$

(d) Diesel oil consumed at port/day in tonnes

$$= 204 \times \text{AUXKW} \times \frac{0.75}{0.95} \times 24 / 10^6 \qquad \text{Eqn. 7.38}$$

where the engine operates at 75% of the maximum continuous rating at sea at an efficiency of 95%.

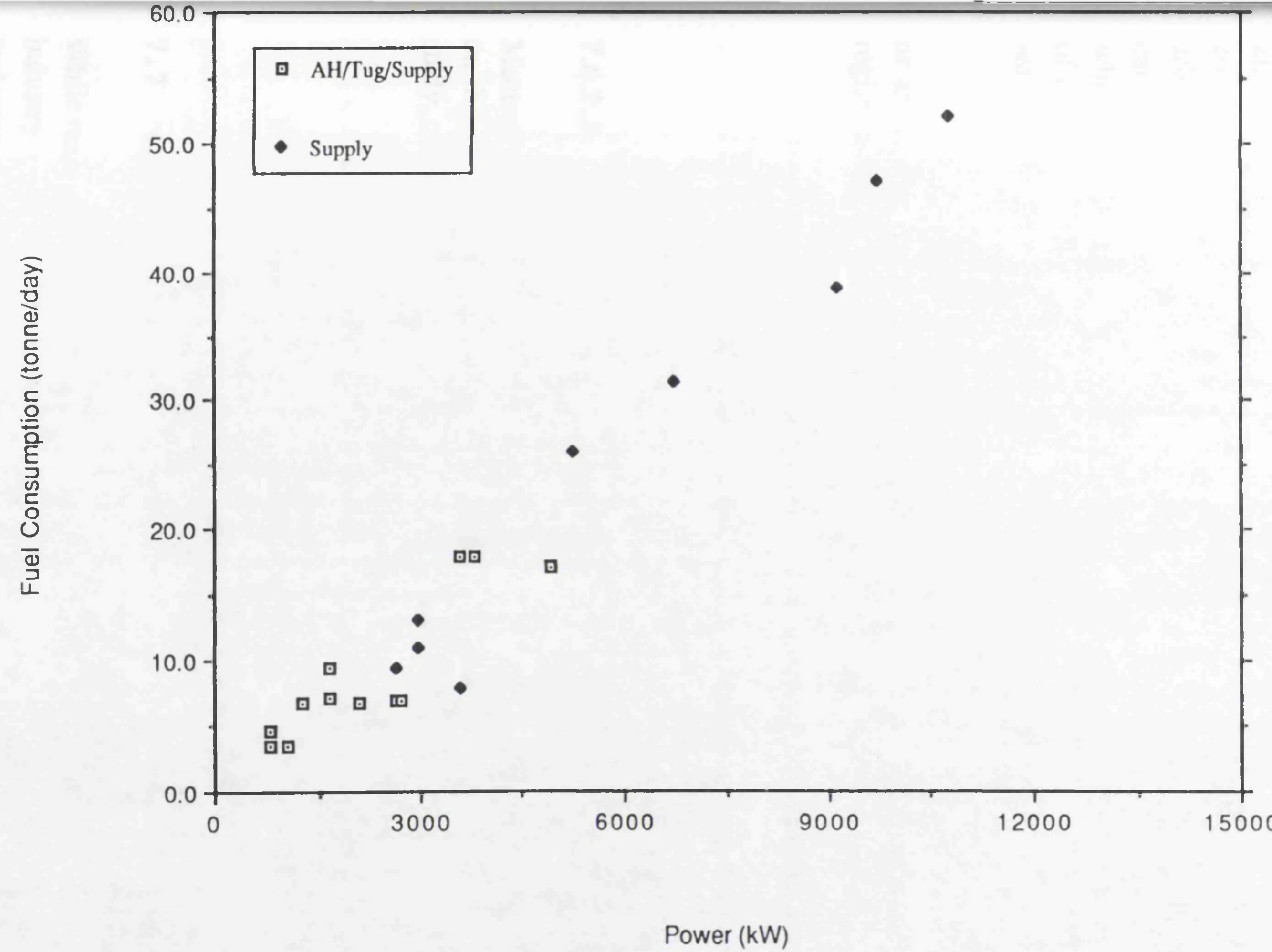

Fig. 7.13 Typical Fuel Consumption Rates for Offshore Supply Vessels Operating in the North Sea [42]

7.6.2.2 Port Charges

Port charges comprise a miscellany of expenses such as port dues, lighthouse dues and port agents' fees. They vary enormously from port to port even in one country, and although some of the differences can be explained logically from the geographical constraints or social economic level of a particular port, a large level of apparently arbitrary variations remain. The shipowners can do very little about these costs as he cannot avoid them, other than electing, if this is possible, to use a competing port where charges are less. However, a faster turn-round service may reduce the amount of these costs as well as a careful voyage scheduling of voyages to avoid unnecessary waiting in ports.

Total port charges are usually expressed as a function of cargo deadmass [31], or as many ports do charge now, they are expressed as a function of net or gross registered tonnage [25], [33]. In this study, port charges are taken as

Port Charges = £(3.0 x Net Registered Tonnage) Eqn. 7.39

7.6.2.3 Cargo Handling Charges

Most offshore supply vessels in service today are not fitted with cargo gear. They rely on shore discharging gear provided by ports of call or by the offshore platform. In this study, cargo handling charges are taken as

Cargo Handling Charges = £(2.0 x Cargo Deadmass) Eqn. 7.40

7.7 CONCLUSION

While reasonable estimates of shipbuilding cost are required by many within the marine industry, only the builder has the cost data to allow as precise as possible a calculation and even so only for his shipyard. Costs are confidential matters and good information is not surprisingly hard to find. It would be an advantage for studies to have access to more cost information but this will remains unlikely apart from the need to have more common demarcation to make comparison possible. This chapter used rather limited data to determine cost but the method used [3] has been found to give acceptable results.

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 operating costs were validated with a limited data base, since shipowners were reluctant to disclose operating costs. However, it is common practice in the offshore supply vessels industry that the shipowner undertakes to provide such vessels for a period of time for use by a charterer. The period of time may be fixed in time, say months or years,perhaps five years. The charterer is thus responsible for arranging voyages and cargoes during such period, while the shipowner will provide the crew and maintain the vessel. In other words, the shipowner will only be responsible for daily running costs, while all voyage expenses, fuel, port charges, and cargo handling costs are to the charterer's account.

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CHAPTER 8

ENGINEERING ECONOMIC ANALYSIS

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8.0 INTRODUCTION

Economics may be defined as the task of allocating a finite supply of investment funds in the face of infinite possibilities while engineering may be defined as the use of scientific knowledge for the benefit of society. Thus, engineering economy is an approach to design aimed at meeting society's needs with a maximum effectiveness in the use of resources such as manpower, materials and investment funds.

The goal of ship design process, as for any engineering design process, may be defined as given a functional requirement (such as transportation of goods from one port to another) which also satisfies a number of constraints of technical, physical or legal nature (stability, strength, safety, classification rules) to seek an optimal technical solution judged on the basis of a definite measure of merit.

This chapter mostly based on [1], [3] and [4] outlines the basic principles regarding engineering economy calculation, the choice of measure of merit and various other economic complexities such as loan, tax, depreciation, and inflation. Taxation, depreciation and tax allowances are calculated for a shipowner building and operating his vessel in the United Kingdom.

8.1 INTEREST RELATIONSHIPS

Investments are made to earn money and their costs can be measured in terms of the required future earnings. In addition to direct outlays there is cost of interest which is forgone on the invested money. Thus the eventual earnings should cover both the cost of regaining the money invested and the forgone interest on that money until it is recovered. The cost of repaying borrowed money is the instalments that repay capital and interest to the lenders. Interest can be divided into two broad categories :

a. contracted interest - used in saving deposits, bank loans, mortgages and bonds which carry mutually agreed interest rates, and

b. implied interest - also known as the lost opportunity interest, which is forgone when the capital is tied up without any resulting interest being earned.

In this study, the former will be used. Such interest may either be simple or compound. In simple interest, the total payments after N years are expressed as

$$F = P(1 + Ni) \qquad \text{Eqn. 8.1}$$

where

F = future sum of money

P = principal or present sum of money

N = number of years of loan, and

i = interest rate expressed as a fraction per annum

Compound interest is the usual method employed for most of the economic studies concerning ship design. The future repayment sum after N years is expressed as

$$F = P(1 + i)^N \qquad \text{Eqn. 8.2}$$

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 [6].

8.2 TIME ADJUSTING MONEY VALUES

In economy studies there are useful applications of compound interest formula that allow all sums of money expected to be involved in a project to be brought to the same point in time, usually time present, generally called present worth.

The interest rate used should represent a base the rate that can be gained by investment with little risk and then increased to allow for the risk and if necessary inflation. The length of time for the project may need to be limited by considerations of obsolescence and altered trading patterns. Generally the formula change the value of single payments with time or convert annuity payments into equivalent lump sums.

8.2.1 Compound Amount Factor and Present Worth Factor

These relationships are used for single payments. The corresponding cash inflows and outflows over time can be conveniently seen in Fig. 8.1. The compound amount factor (CA) is the multiplier to convert a present value into a future value and expressed as

$$F = (CA) \times P \qquad \text{Eqn. 8.3}$$

where

$$CA = (1 + i)^N$$

If the interest is compound T times per year, with the interest rate expressed annually as i, then

$$CA = (1 + i/T)^{NT} \qquad \text{Eqn. 8.4}$$

The reciprocal of the compound amount factor is known as the present worth factor (PW), which is the multiplier to convert a future sum into present sum and expressed as

$$P = (PW) \times F \qquad \text{Eqn. 8.5}$$

where

$$PW = \frac{P}{F} = \frac{1}{CA} = (1 + i)^{-N} \qquad \text{Eqn. 8.6}$$

8.2.2 Capital Recovery Factor and Series Present Worth Factor

These relationship are used for series payments and are shown diagrammatically in Fig. 8 2. For a loan repaid by a 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 the usual method with shipbuilding loans, and

b. uniform payments, which is the usual method for leasing and mortgages, predominantly interest in early years, and repayments of principal in later years.

The capital recovery factor (CR) is used to convert an initial capital investment to an equivalent annual capital charge, which includes both the principal and the interest. It is the relationship between the uniform annual amount (A) and the principal (P) and expressed as

$$A = (CR \times P) \qquad \text{Eqn. 8.7}$$

where

$$CR = \frac{i}{1-(1+i)^{-N}} \qquad \text{Eqn. 8.8}$$

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

$$P = (SPW) \times A \qquad \text{Eqn. 8.9}$$

where

$$SPW = \frac{P}{A} = \frac{1}{CR} = \frac{(1+i)^N - 1}{i(1+i)^N} \qquad \text{Eqn. 8.10}$$

8.2.3 Sinking Fund Factor and Series Compound Amount Factor

These two factors are less frequently used in marine industries. The sinking fund factor (SFF) enables a future sum of money to be converted into a regular (annual) amount of money at equal intervals, see Fig. 8 3, and is expressed as

$$A = (\text{SFF}) \times F \qquad \text{Eqn. 8.11}$$

where

$$\text{SFF} = \frac{A}{F} = \frac{i}{(1.0 + i)^N - 1} \qquad \text{Eqn. 8.12}$$

The reciprocal of the sinking fund factor is the series compound amount factor (SCAF) which is the multiplier to convert a regular amount of money into a future sum of money and is expressed as

$$F = (\text{SCAF}) \times A \qquad \text{Eqn. 8.13}$$

where

$$\text{SCAF} = \frac{A}{\text{SFF}} = \frac{(1.0 + i)^N - 1}{i} \qquad \text{Eqn. 8.14}$$

8.3 ECONOMIC MEASURE OF MERITS

There are various different measures of merit used in ship design studies. Four most commonly used are shown in Table 8.1. *Buxton* [1], *Goss* [3], *Oostinjen* [26], *Benford* [4], [15], and *Hettena* [25] gave the advantages and disadvantages of the various measures of merit. General equations on the calculation of the measures of merit are given below. Details on such measures of merit are given by *Buxton* [1] and *Benford* [15], or any other standard textbook on capital investment [27].

187.

$$\text{Net Present Value} = \sum_0^N \left[PW_{cq} - PW_{oc} - PW_{ac} \right] \qquad \text{Eqn. 8.15}$$

$$\text{Required Freight Rate} = \sum_0^N \left[\frac{PW_{oc} + PW_{ac}}{PW(\text{annual cargo quantity})} \right] \qquad \text{Eqn. 8.16}$$

$$\text{Average Annual Cost} = \sum_0^N \left[PW_{oc} + PW_{ac} \right] \qquad \text{Eqn. 8.17}$$

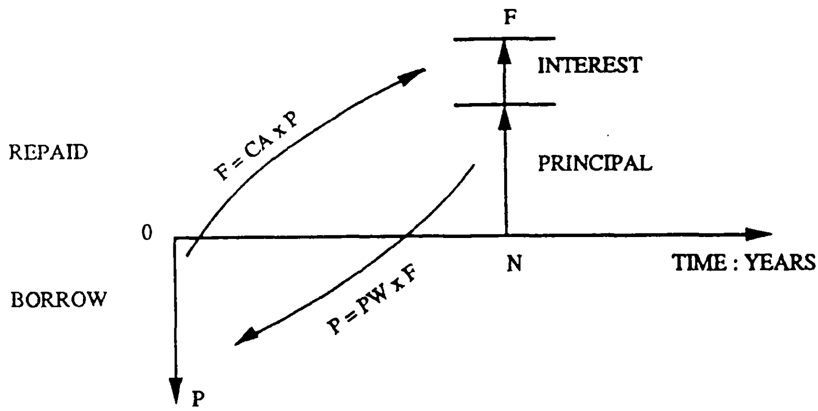


Fig. 8.1 Compound Amount Factor and Present Worth Factor

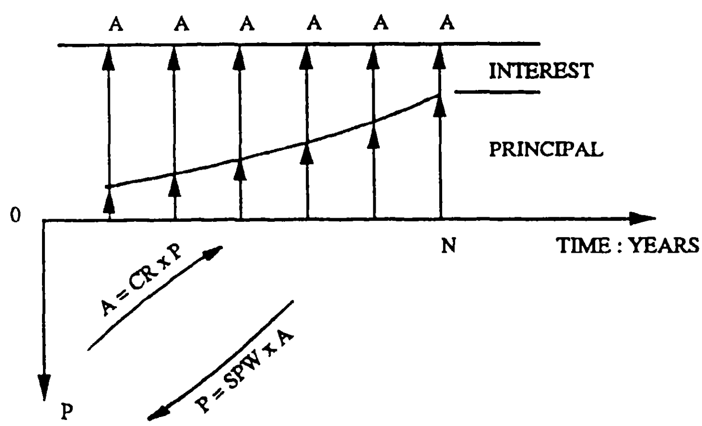


Fig. 8.2 Capital Recovery Factor and Series Present Worth Factor

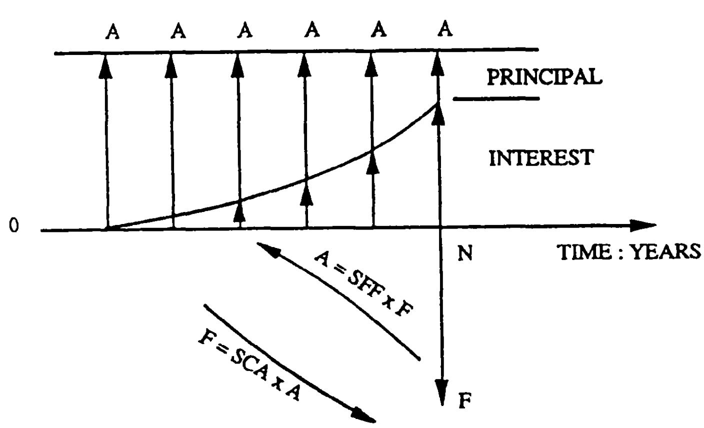


Fig. 8.3 Sinking Fund Factor and Compound Amount Factor

where

PW_{cq} = annual cargo quantity x freight rate

PW_{oc} = annual operating costs

PW_{ac} = ship acquisition costs

Figure 8.4 gives a decision chart which can be used for selecting a measure of merit, depending on the type of input data available at the preliminary design stage.

8.4 ECONOMIC COMPLEXITIES

Whereas in simple short cut studies, uniform cash flows can be assumed and economic complexities like tax, depreciation and inflation incorporated in interest relationships like CR and SPW, a year to year calculation is preferred to correctly assess the influence of tax allowances such as depreciation and interests on loans. Thus, in this study, computer programs have been written for ships built under the United Kingdom tax regime and a shipowner utilising domestic credit terms offered by the government.

8.4.1 Loans

Most countries throughout the world offers loans for ships purchase through their central sources. These loans at reduced rates of interest are made available in order to stimulate the shipbuilding industries and encourage owners to place orders.

Typical values for shipbuilding industry are loans around 80% of the capital cost for a duration of 8 to 8.5 years repayable at an interest rate of 7.5%. Generally the loan or credit is advanced to the shipowner in several instalments with interest made payable before the ship delivery. Repayment of the loan is usually in equal amounts, at six-monthly or annual intervals after delivery, plus interest on the declining balance.

8.4.2 Tax

Taxes generally have pronounced effects on the final selection of design alternatives. It should always be accounted for in the final evaluation of a project since it may greatly reduce the net income.

Table 8.1 Typical Economic Measures of Merit

Measure of Merit	Definition	Maximise or Minimise
Net Present Value	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.	Maximise
Internal Rate of Return	The interest rate that brings the net present value to zero.	Maximise
Required Freight Rate	The unit charges to customer that must be earned if the owner is to gain a reasonable yield on investment.	Minimise
Average Annual Cost	A uniform annual expense equalled in present value to the investment and the operating costs. Discounts future amounts at an interest rate reflecting the investor's time value of money.	Minimise

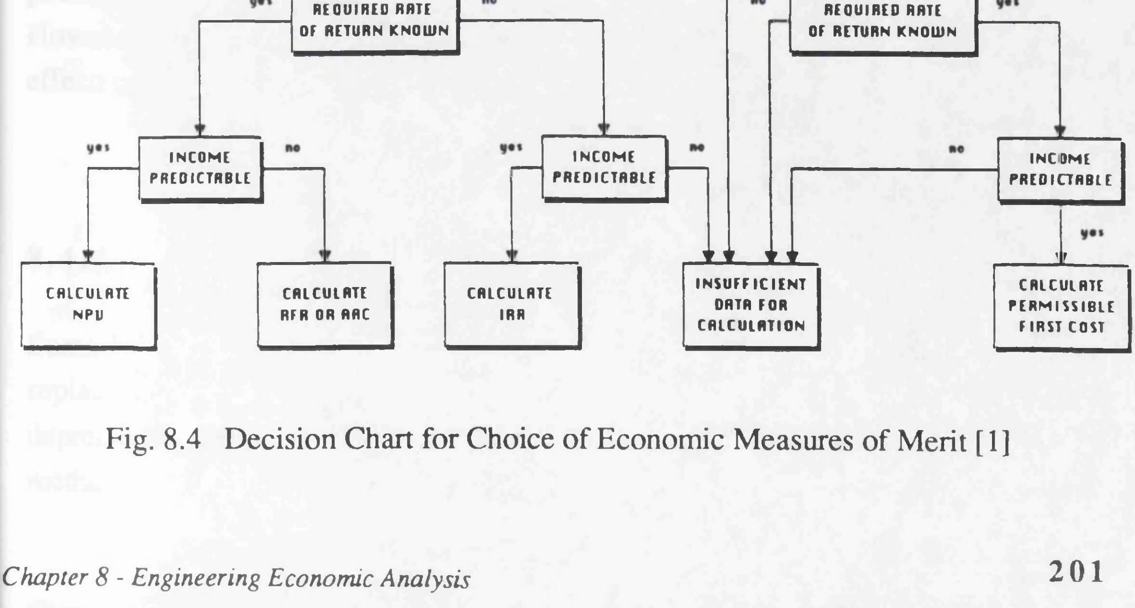


Fig. 8.4 Decision Chart for Choice of Economic Measures of Merit [1]

According to *Benford* [2], when income can be predicted, decisions can usually be made on the basis of returns before tax since the best design before tax is usually the best design after tax. However, when income cannot be predicted, which is usually the case, the calculation of AAC or RFR must be based on the owner's stipulated yield corrected for tax.

The present rate of corporation tax in the United Kingdom is 35%.

8.4.3 Inflation

In real economic life, all the shipowner's expenses as well as his income may be subjected to a rise over the years. Thus, in an economic study evaluations may either be carried out in real terms (that is with constant purchasing power) or money terms (that is including an allowance for inflation). The former method appears to be less realistic but it gives acceptable results as long as the discount rate used is properly defined as inflation is essentially an increase in rate and only differential inflation among components needs serious treatment.

Most economic evaluations of ships use money rather than real terms. Use of money terms means that it is easier to incorporate the almost universal use of shipbuilding loans, it uses units that the ship operator uses in his own projection, it allows tax considerations to be included and it forces an attention on escalation rates for costs and freight revenue.

Inflation can be neglected when income and costs rise at the same rates. This is possible as long as the shipowner is free to raise his prices to offset his rising costs. However, a high inflation rate is found to reduce the shipowner's yield and increase his effective tax rate [28]. Table 8.2 shows this trend of escalation rates of operating costs.

8.4.4 Depreciation

Some formal arrangement must be made for depreciation to ensure that it is possible to replace old vessels and that taxes are correctly levied. there are different types of depreciation patterns such as straight-line, declining balance and free depreciation. The method chosen for tax purposes must be approved by the taxation authority.

Straight-line depreciation may be assessed as the ship cost over expected ship life. The declining balance depreciation, which is is now used in the United Kingdom, makes the annual allowance for depreciation to be a percentage of the residual value each year. Free depreciation allows the cost of the ship to be written off against tax as fast as profits permit and may be immediate if there are enough profits. This is the most attractive method to the owners. Comparison of the various depreciation methods is given in Fig. 8.5.

8.5 EVALUATION OF CAPITAL CHARGES

Once the cost of building the ship is estimated, the builder's account can be manipulated as shown in Fig. 8.6. It uses as input the capital cost of the ship, discount rate in percentage interest on loan repayment and the number of years of repayment of loan. The procedure given by Buxton [1] is followed with several assumptions as given :

a. The loan taken by the shipowner to finance the ship is 70% of the capital cost while the remaining 30% is assumed to be provided from the owner's own account.

b. The number of years of loan is 8 years and the interest on the loan is 8% per annum.

c. The discounting is done with a discount rate of 10% per annum.

d. Year 0 is the year contract is signed and the ship delivered in the end of the sixteen months.

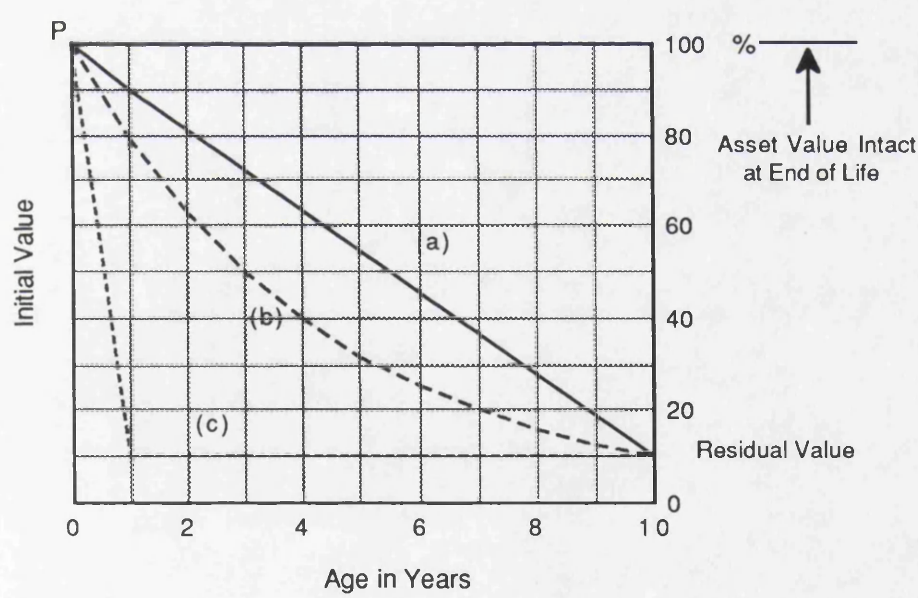
e. Building instalments are as follows : 30% when the contract is signed, 15% when the keel is laid (that is year 1.0), 50% when launched (that is year 1.25), and 5% when delivered.

f. The loan is repaid in equal instalments over the period of the loan and is paid every year.

Table 8.3 shows for an offshore supply vessel, the building account based on the above assumptions, the same procedure is fulfilled in the algorithm. The program was validated by carrying out step by step hand calculation.

Table 8.2 Yield and Effective Tax Rate Under Various Levels of Inflation (Straight Line Depreciation) [28]

Assumed Annual Rate of Inflation (%)	Derived Value of Yield (%)	Effective Tax Rate (%)
0.0	11.10	50.00
8.0	9.90	56.50
12.0	9.50	58.50
16.0	9.30	59.60
20.0	9.10	60.60
24.0	8.90	61.30



* a = straight line
b = declining balance
c = free depreciation to residual value with delay of one year

Fig. 8.5 Comparison Between Different Types of Depreciation [27]

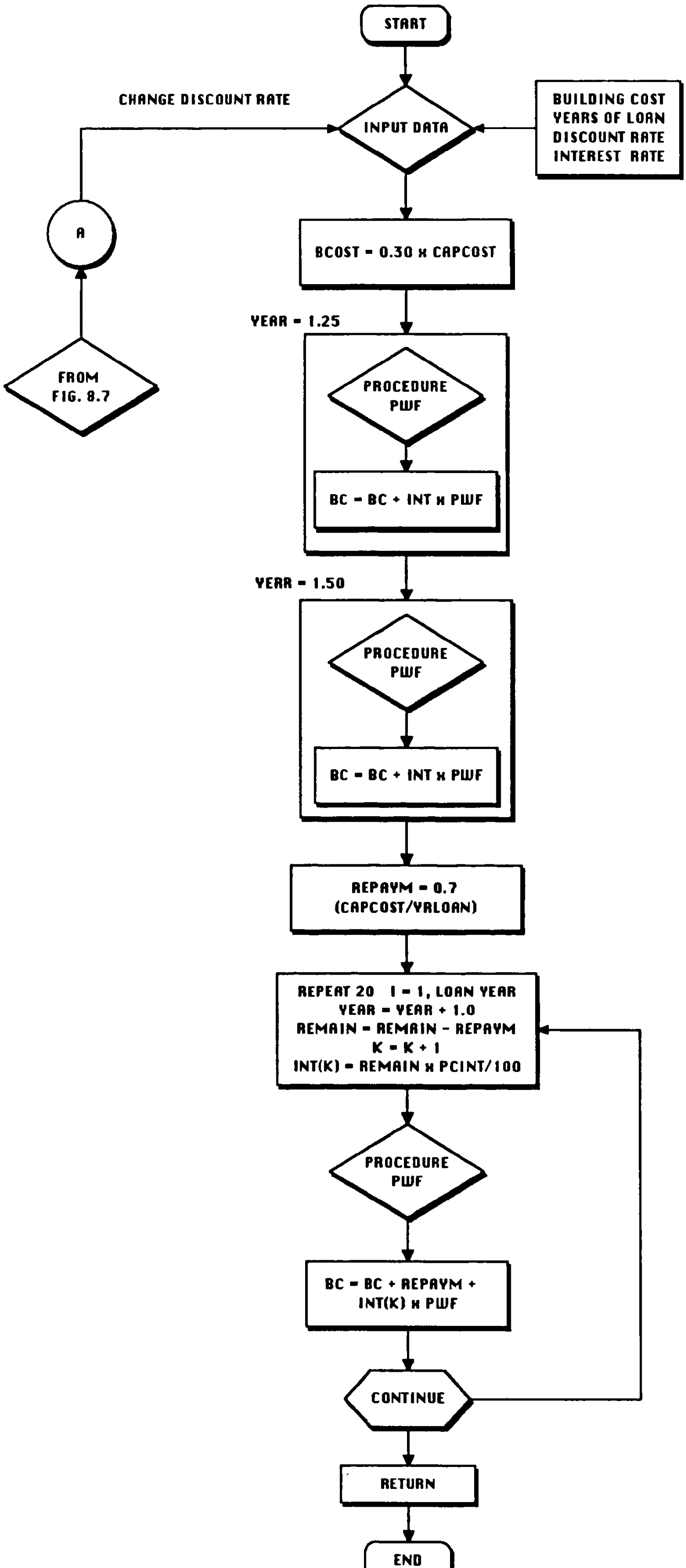


Fig. 8.6 Flowchart for Evaluation of Capital Charges

Table 8.3 Typical Example of Builder's Account

Year	Building Installment	Owner's 30%	Loan Drawdown	Loan Repayment	Loan Outstanding	Loan Interest 8%	Owner's Cash Flow	PW Factor 10%	Discounted Cash Flow
0.0	2400	2400					2400	1.0000	2400.00
1.0	1200		1200		1200			0.9090	
1.25	4000		4000		5200	24	24	0.8877	21.31
1.5	400		400		5600	104	104	0.8668	90.15
2.5				700	4900	448	1148	0.7880	904.62
3.5				700	4200	392	1092	0.7163	782.20
4.5				700	3500	336	1036	0.6512	674.64
5.5				700	2800	280	980	0.5920	580.16
6.5				700	2100	224	924	0.5382	497.30
7.5				700	1400	168	868	0.4893	424.71
8.5				700	700	112	812	0.4448	363.78
9.5				700	0	56	756	0.4044	305.73
Total	8000		5600	5600		2144	10144		7044.6

* Costs are in thousands £ Sterlings

8.6 ANALYSIS OF DAY RATES

Since the offshore industry's peak in 1982-83 and the market's low point of mid 1987, various self correcting features and aggressive reorganisations have helped the United Kingdom offshore supply vessel industry weather the storm. In spite of continuing price squeezing by operators and the limited borrowing power of contractors, a market recovery is underway, with business on the increase at an accelerating pace. Rising day rates and utilisation are the most obvious and encouraging indicators.

The North Sea, with over 200 offshore supply vessels operating, is second only to the United States Gulf, as an offshore market. Though more mundane than some sectors of the United Kingdom trading fleet, offshore supply vessels nevertheless perform an essential service to the North Sea oil and gas industry.

Offshore supply vessels are operated on either a spot or long term charter basis. The spot market, normally involving durations of up to 30 days, is a volatile one, usually, usually characterised by high day rates and mainly rig moving. As demand for spot market market vessels increases so inevitably does the day rates. The long term charter market tends to be dominated by operators who have a number of fields to service and substantial exploration programmes, both of which merit fleet charters ordered in advance. Most of the major oil companies deploy fleets of offshore supply vessels on a long term basis for all their activities, other than rig moves.

Day rates are just beginning to reach levels achieved in 1986/87 just prior to oil price collapse. Vessel owners are now doing what they can to push up prices and recoup losses incurred over the last few years. The larger supply vessels are likely to continue to increase their market dominance. The almost universal requirement for the more powerful vessel and their operational advantages, high mud and liquid carrying capacity, longer endurance, and better seakeeping are edging smaller vessels out of the market. Table 8.4 shows the trend of day rates for anchor handling/tug/supply vessels and pure offshore supply vessels operating in the North Sea obtained from various sources..

8.6.1 Evaluation of Measure of Merit for Offshore Supply Vessels

The internal rate of return and required freight rate will be taken as the economic measure of merit in this study. Since the cash flows are not uniform, the calculations are carried out year by year from the year of delivery (year 1.5). The flowchart for IRR algorithm adopted is shown in Fig. 8.7 and the main steps will be described below.

Table 8.4 Day Rates for Offshore Supply Vessels Operating in the North Sea
(Figures are in UK Pound Sterling)

YEAR	ANCHOR HANDLING/TUG/SUPPLY			PURE SUPPLY	
	5000 - 8000 BHP	8000 - 10000 BHP	10000 - 15000 BHP	BUILT 1975 - 1982	BUILT 1982 ONW.
1984	2500 - 3000	3000 - 3500	4000 - 6000	2000 - 2500	2800 - 3500
1985	2750 - 3450	3300 - 3875	4400 - 6900	2200 -2875	3800 - 4025
1986	1000 - 1200	1500 - 2000	2500 - 2750	1000 -1500	2400 - 3000
1987	1200 - 1500	1800 - 2200	2500 - 2750	1000 - 1500	2500 - 3200
1988	1800 - 2150	2200 - 2500	2500 - 2750	1500 - 1750	1800 - 2150
1989	1800 - 2200	2200 - 2500	3000 - 4250	1800 - 2150	2000 - 2500
1990	2000 - 2500	2400 - 2750	4000 - 4500	2000 - 2300	2350 - 2800
1991	2450 - 2800	2600 - 2900	4250 - 4800	2250 - 2500	2750 - 3200
1992	3000 - 3500	3000 - 3500	5000 - 5500	2400 - 2750	4000 - 4500

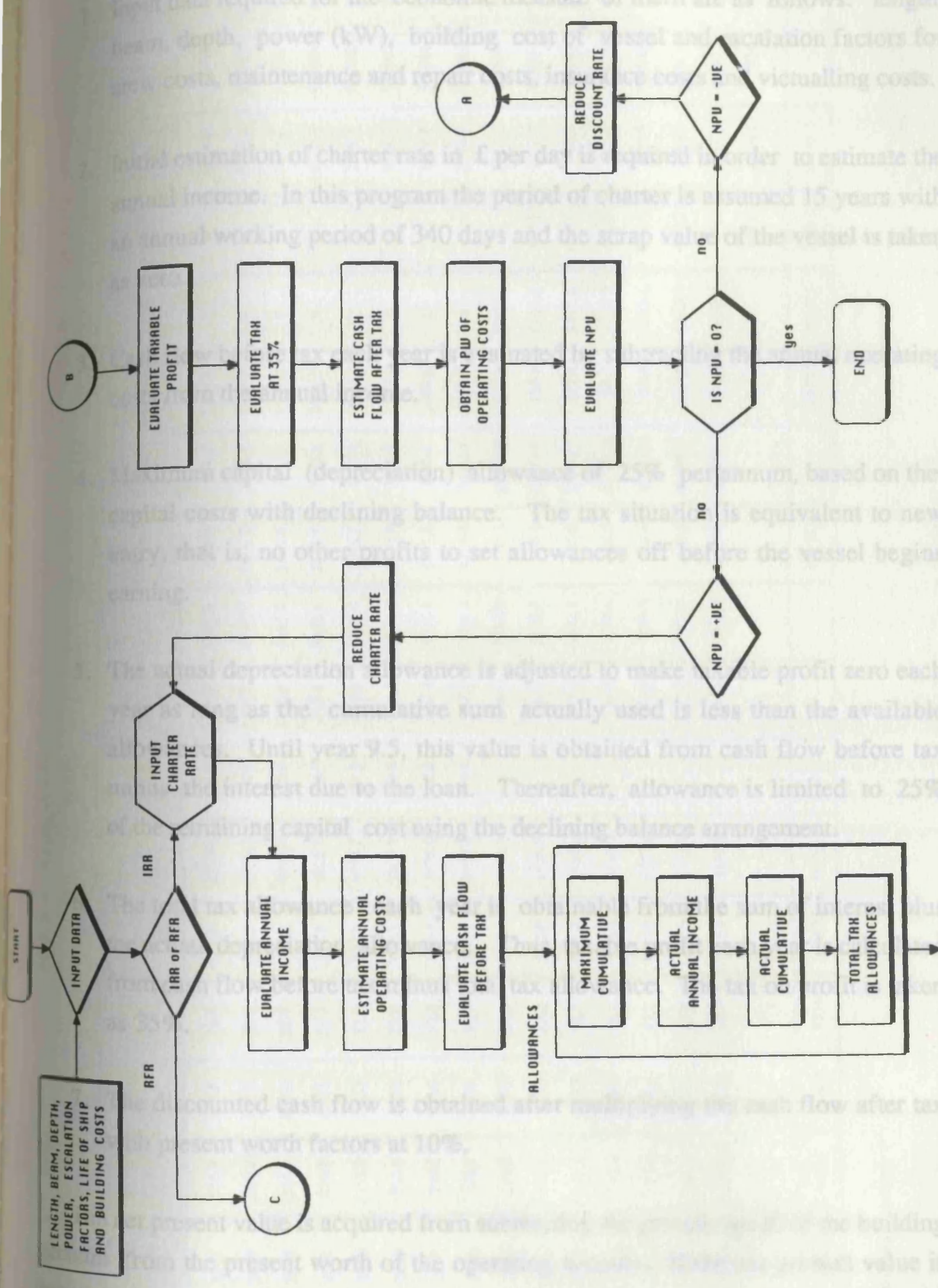


Fig. 8.7 Flowchart for Calculating Internal Rate of Return

1. Input data required for the economic measure of merit are as follows: length, beam, depth, power (kW), building cost of vessel and escalation factors for crew costs, maintenance and repair costs, insurance costs and victualling costs.

2. Initial estimation of charter rate in £ per day is required in order to estimate the annual income. In this program the period of charter is assumed 15 years with an annual working period of 340 days and the scrap value of the vessel is taken as zero.

3. Cash flow before tax each year is evaluated by subtracting the annual operating costs from the annual income.

4. Maximum capital (depreciation) allowance of 25% per annum, based on the capital costs with declining balance. The tax situation is equivalent to new entry, that is, no other profits to set allowances off before the vessel begins earning.

5. The actual depreciation allowance is adjusted to make taxable profit zero each year as long as the cumulative sum actually used is less than the available allowances. Until year 9.5, this value is obtained from cash flow before tax minus the interest due to the loan. Thereafter, allowance is limited to 25% of the remaining capital cost using the declining balance arrangement.

6. The total tax allowance each year is obtainable from the sum of interest plus the actual depreciation allowance. Thus, taxable profit each year is calculated from cash flow before tax minus total tax allowance. The tax on profit is taken as 35%.

7. The discounted cash flow is obtained after multiplying the cash flow after tax with present worth factors at 10%.

The net present value is acquired from subtracting the present worth of the building account from the present worth of the operating account. If the net present value is negative, the investment yields less than the percentage rate of return expected whereas if the net present value is too much on the positive side,it may indicate that the charter rate is too high and the vessel may not be chartered. Table 8.5 gives an example of an owner's operating account.

Table 8.5 Typical Example of Owner's Operating Account

Year	Annual Income	Crew Costs	M & R Costs	Other Costs	Annual Operating Costs	Cash Flow Before Tax	TAX ALLOWANCES						Taxable Profit	Tax at 35 %	Cash Flow After Tax	PWF 10%	DCF
							Interest	25% Annual	Max. Cum.	Actual Annual	Actual Cum.	Total Tax Allow.					
2.5	2040	316.8	149.5	19.4	485.7	1554.3	576.0	2000.0	2000.0	978.3	978.3	1554.3	0	0	1554.3	0.7880	1224.8
3.5	2040	316.8	157.0	20.0	493.8	1546.2	392.0	1500.0	3500.0	1154.2	2132.5	1546.2	0	0	1546.2	0.7163	1107.5
4.5	2040	316.8	164.8	20.6	502.2	1537.8	336.0	1125.0	4625.0	1201.8	3334.3	1537.8	0	0	1537.8	0.6512	1001.4
5.5	2040	316.8	173.1	21.2	511.1	1528.9	280.0	843.8	5468.8	1248.9	4583.2	1528.3	0	0	1528.3	0.5920	904.8
6.5	2040	316.8	181.7	21.8	520.3	1519.7	224.0	632.8	6101.6	1295.7	5878.9	1519.7	0	0	1519.7	0.5382	817.9
7.5	2040	316.8	190.8	22.5	530.1	1509.9	168.0	474.6	6576.2	1341.9	7220.8	1509.9	0	0	1509.9	0.4893	738.8
8.5	2040	316.8	200.4	23.2	540.4	1499.6	112.0	355.9	6932.1	1387.6	8608.4	1499.6	0	0	1499.6	0.4448	667.0
9.5	2040	316.8	210.4	23.9	551.1	1488.9	56.0	267.0	7199.1	1432.9	10041.3	1488.9	0	0	1488.9	0.4044	602.1
10.5	2040	316.8	220.9	24.6	562.3	1477.7		200.2	7399.3	200.2	10241.5	200.2	1277.5	0	1477.7	0.3676	543.2
11.5	2040	316.8	231.9	25.3	574.0	1466.0		150.2	7549.5	150.2	10391.5	150.2	1315.8	447.1	1017.9	0.3342	340.2
12.5	2040	316.8	243.5	26.1	586.4	1453.6		112.6	7662.1	112.6	10504.1	112.6	1341.0	460.5	993.1	0.3038	301.7
13.5	2040	316.8	255.7	26.8	599.3	1440.7		84.5	7746.6	84.5	10588.6	84.5	1356.2	469.4	971.3	0.2762	268.3
14.5	2040	316.8	268.5	27.7	613.0	1427.0		63.4	7810.0	63.4	10652.0	63.4	1363.6	474.7	952.4	0.2510	239.1
15.5	2040	316.8	281.9	28.5	627.2	1412.8		47.5	7857.5	47.5	10699.5	47.5	1365.3	477.3	935.5	0.2283	213.6
16.5	2040	316.8	296.0	29.3	642.1	1397.9		35.6	7893.1	35.6	10735.1	35.6	1362.3	477.9	919.9	0.2075	190.9
														476.8	- 476.8	0.1886	- 89.9
Total	30600	4752	3226.1	8339	16317.1	14282.9	2144			10735.3		12878.7	9381.7	3283.7	18975.7		9071.4

Costs in Thousand £ Sterlings

Figure 8.8 shows flow chart for the required freight rate algorithm. Using the present worth of building account caculated earlier, the freight rate before tax is given by

CFR = (PW operating cost + PW building cost)/(PW cargo deadmass) Eqn. 8.18

To determine the exact freight rate which determine zero NPV, the whole procedure is repeated for two other values of CFR, 1.2 CFR and 0.8 CFR, which gives two other values of NPV. Using Lagragian interpolation, the required freight rate giving zero NPV is determined.

8.7 CONCLUSION

The technical and economic considerations in the preliminary design of ship are indivisible. Ship design is not an isolated science divorced from economic considerations. A commercial ship such as offshore supply vessel is not an engineering success unless it is also a potentially profitable investment. Profitability is related to technical characteristics, and these relationships should be understood by the designer. This chapter has described an outline of an economic method applicable to the preliminary design of offshore supply vessel, pointing out the choice of criterion to be selected can be internal rate of return if revenues are predictable or required freight rate if revenues are unpredictable. More detailed studies on the operational costs from the charterer's view point will be discussed in the following chapter.

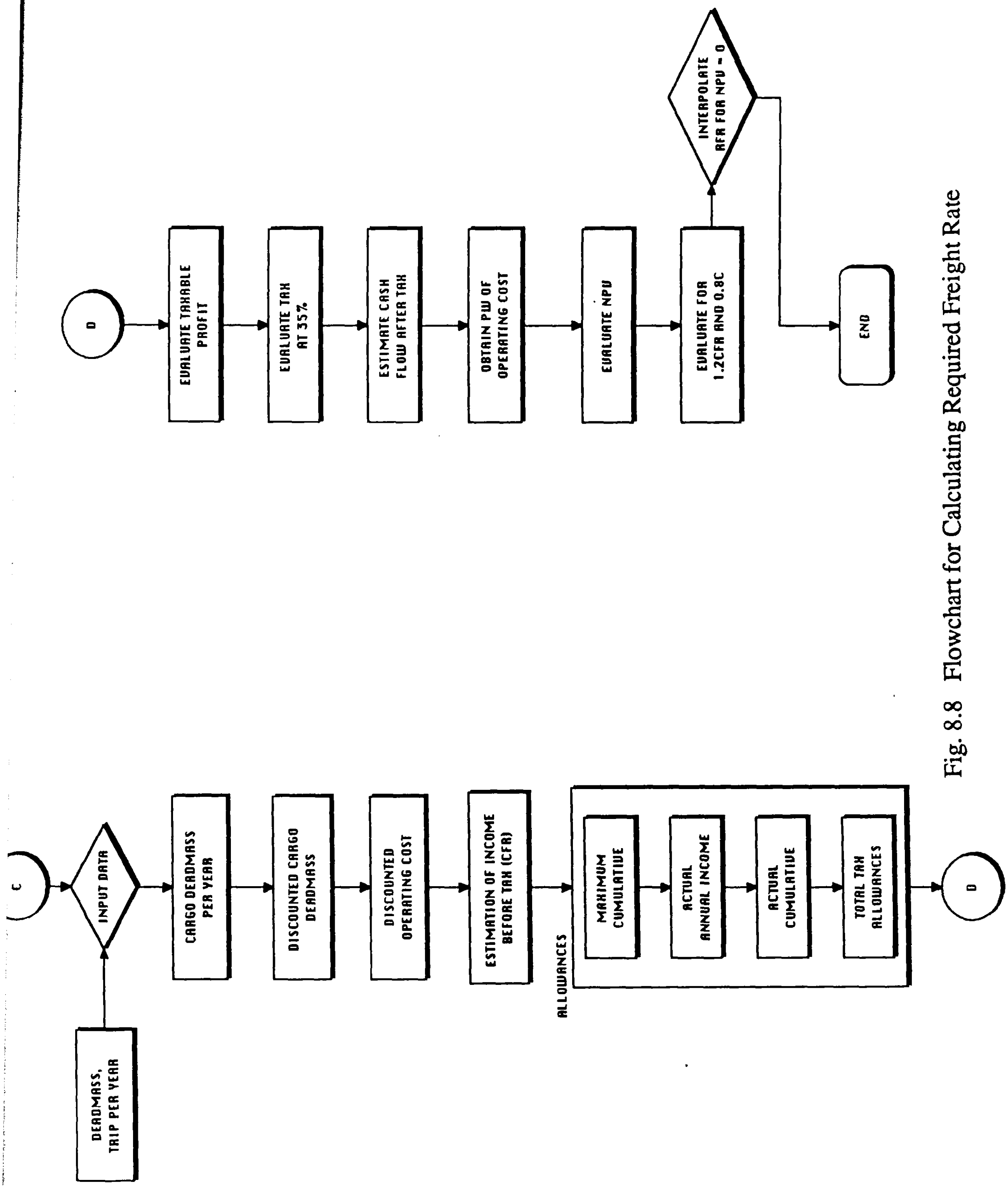


Fig. 8.8 Flowchart for Calculating Required Freight Rate

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CHAPTER 9

MODELLING THE OPERATION OF OFFSHORE SUPPLY VESSELS

CHAPTER 9

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9.0 INTRODUCTION

Offshore supply vessels are vessels whose primary role is to provide services to other independent systems with their own objectives. Often the demand for such vessels is sporadic and can only be defined in a probabilistic way. Also it is not uncommon for the operating activities of such vessels to be affected by prevailing weather more significantly than many conventional vessels. Thus modelling of the operating pattern of the offshore supply vessels is complex.

The success or otherwise for offshore supply vessels comes from their ability to provide an adequate service on demand and inability to provide such service normally results in economic loss for the system being served. In short, the difficulties which are encountered when trying to carry out conventional ship design studies for offshore supply vessels are :

a. considerably greater attention needs to be given to the operating model of the vessel, and

b. the probabilistic nature of the parameters of the operations needs to be taken into account.

The approach suggested in this study to overcome these difficulties consists of the use of computer-based simulation approach to model the operating pattern and thus allow the introduction of probabilistic factors.

9.1 BACKGROUND ON OFFSHORE SUPPLY OPERATIONS

A drilling rig consumes large quantities of materials during the drilling of an offshore well, yet the rig does not have sufficient space or payload capacity to accommodate all the materials it requires during such an operation. In the case of mobile drilling units (semi-submersibles, drillships and jack-ups), there is a clear limitation on the payload, usually known as variable deck load.

The supply operation is involved with the transportation of materials and equipment to the offshore drilling rig by supply vessels. In logistic terms, the supply operation is simple enough, but wind, tide and sea conditions make the overall exercise difficult and expensive to implement. Bad weather whether it be waves, wind or fog will reduce the speed of the supply vessel and may prevent or delay discharge of its cargo to the rig. As a result, the supply of materials to a rig can be erratic. The supply operation must also be able to respond to failure of essential drilling equipment, which can occur randomly, and resupply the equipment in order to keep rig downtime to a minimum.

If an operation is overdesigned, the costs of setting up and running the operation will be high. On the other hand, if an operation in underdesigned, the costs incurred due to inadequacies in the operation will be high. Hence, for an optimum supply system, the sum of these costs should be a minimum, although the gainer and loser if this is not the case may be different organisations.

9.1.1 Consumption of Materials

The materials consumed in the drilling of an offshore oil well and the pattern in which they are consumed depends on the drilling process and the drilling requirements. Average material consumption for completing an exploration well of depth 3353 m in the North Sea is shown in Table 9.1 [10].

9.1.1.1 Drilling Process

Drilling an offshore oil well is a complex and dangerous task. The problems that can be encountered include caving in of the bore hole, or fluids from upper formations may pour down hole and spoil the oil sands. To guard against such mishaps, drilling has to be stopped at intervals and the drill pipe removed from the well so that the hole may be lined with steel casing securely set in cement. Drilling then continues with a smaller bit which will go down inside this casing. Later on, at a greater depth, another length of casing may be inserted inside the first length, and possibly a third length inside this second. Thus the requirement for casing and cement are directly related to the hole diameter and the depth of the drill hole. Another important feature of the drilling process is the circulation of the drilling fluid, which is called drilling mud, a mixture of either barytes and water or barytes and diesel oil. The principal uses of drilling mud include removing the cuttings, lubricating the drill bit, sealing the sides of the hole, as well as allowing deliberate variation in density to keep the pressure within the well in balance. While mud is recirculated after sieving, there will be a steady consumption of its components as the hole elongates and losses to the wall take place.

The drilling rig also requires fuel, potable and other water, equipment and spare parts, normal provisions and stores for the crews on board.

9.1.1.2 The Drilling Requirements

From the brief description of the drilling process, the major types of materials required for the drilling of an offshore well have been identified which can be categorised as drilling equipment, down hole consumables, rig consumables and life support requirements.

The drilling equipment include drill-strings, associated fittings, drill bits of different sizes, various workover tools, guide base fittings, and drill machine replacements. While much spare equipment for breakdown is kept on the drilling rig, there needs to be quick response in circumstances where new equipment must be brought out to the rig to avoid interruption of drilling, and needs ready availability of a supply vessel.

The down hole consumables include those items which are consumed in drilling a well, such as casing of various sizes, cement, mud, additives and drill water. These requirements are most important to the supply operation since they constitute the major part of the materials to be transported. The rate of consumption of these items depends on the characteristics of the hole and the offshore activity phase. The area characteristics affect the consumption pattern in that they dictate the depth at which the casing is set and also the size of the casing. The mud consumption is also affected by the area characteristics. The different activity phases influence the consumption pattern, where in exploration drilling progress is slow because of the unpredictable nature of the structure while in development drilling, the same materials are consumed at a faster rate since the drilling process is more predictable.

The rig consumables are like those of any ship where the main consumption is fuel, the requirement for which is steady and predictable and does not pose any great problem to the supply operation. However, any shortage of fuel would stop the drilling operation. Life support requirements include those items that are consumed by

Table 9.1 Material Requirements for Completing an Exploration Well in the North Sea

Item	Steel	Cement	Mud
	(tonnes)		
Drill Bits	14.9		
Wire String	15.7		
Drilling Mud			1016.0
Cement		406.4	
Drill Collars	1.5		
Conductor	3.6		
Casing	517.0		
Blowout Preventor	3.5		
Drill Pipe	2.9		

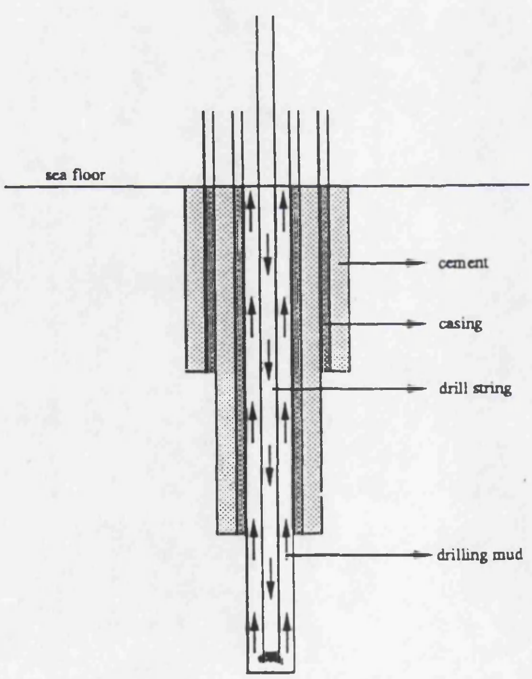

Fig. 9.1 Typical Drill Hole Section

the personnel on board the rig. Such items can be identified as food, domestic stores, and fresh water. These items are predictable and can easily transported in containers.

9.1.2 Drilling Rigs

There are several types of vessel used for offshore drilling for oil. They include self-elevating (jack-ups) platforms, semi-submersibles and monohulls either barges or drill ships. Jack-ups are limited by the current length of their legs to about 100 metres depth of water. Monohulls have a more restricted weather window than semi-submersibles because of their seaway motion characteristics. However they have large values of variable deck load in proportion to their size and are usually chartered for work in remote areas with relatively good weather where supply is difficult. Semi-submersibles are best for bad weather but with modest variable deck loads compared to displacement, thus they need frequent supply. Production platforms also drill new wells and need the services of supply vessels. Deeper waters have promoted the use of floaters either monohulls or semi-submersibles or tension leg platforms as production platforms. Table 9.2 gives some storage capacities for different types of rig.

9.1.3 Supply Base

The objective of an offshore supply base is to offer complete harbour facilities and onshore services to those companies involved in the continental shelf exploration and production programmes. The requirements for an offshore supply base can be divided into two main categories, that is, fundamental and secondary.

Fundamental requirements are facilities which are essential to the operation of a base and cannot be installed or constructed in a short time or without considerable expenditure. These include a sheltered all weather harbour, storage space (both indoors and outdoors), sufficient local labour, and an adequate transport system. An all weather harbour is essential to an efficient supply operation if the base is to be operational 24 hours a day the whole year round. In the northern section of North Sea, there are generally two supply vessels per rig. If operations are busy in an area serviced by one base, then lots of quay space is needed to avoid longer queuing time for loading the materials. Some of the larger bases servicing the North Sea have facilities for more than 15 vessels to load and unload simultaneously. A good transport system is important, since heavy pieces of equipment have to be brought into the base by rail or truck. Adequate storage areas are needed to keep material in readiness. One estimate is that two acres are required to support one exploration well [6].

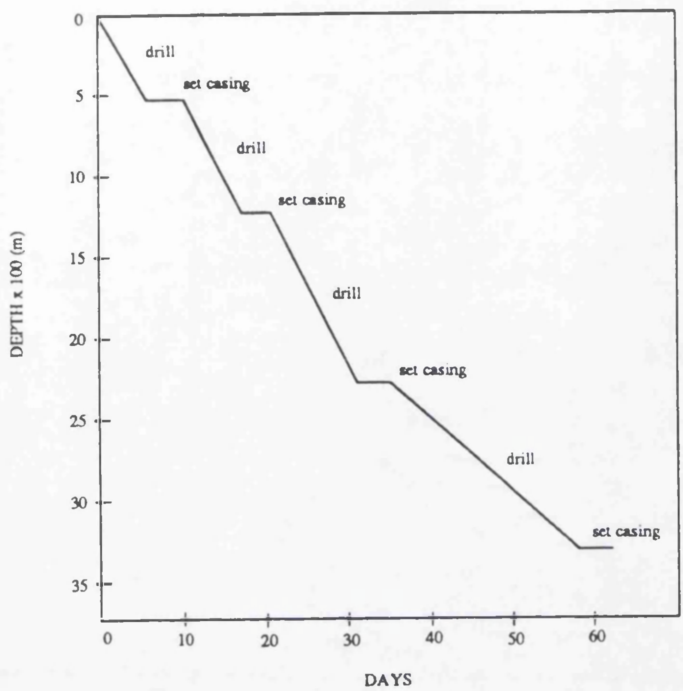

Fig. 9.2 Typical Drilling Schedule for an Offshore Well

Table 9.2 Storage Capacities for Different Type of Rigs

Type of Rig	Dry Bulk Mud/Cement (m^3)	Liquid Mud (m^3)	Fuel Oil (m^3)	Potable/Drill Water (m^3)	Pipe (tonnes)
Semi-submersible	320	330	1000	1500	500
Jack-Up	190	220	570	850	300
Drill Ship & Barges	320	510	1500	2100	600

The secondary requirements include cranes and other loading equipment, a fuel supply, a fresh water supply, the presence of supply and service companies, workshop facilities, communication facilities, clerical services, and first aid services.

From the above factors, it can be observed that supply bases play an important role in the whole supply operation and represent a fairly expensive part of the whole offshore development programme.

9.2 APPROACH TO STUDYING SUPPLY OPERATIONS

From the description of the characteristics of the supply operation, it has been observed that any studies in this area must take into account many technical, operational and economic factors. The model to be constructed must take account of all factors influencing the operation which will include the technical model, operational and economic models.

The technical model consists of the characteristics of the offshore supply vessels which are vital for the operational and economic aspects of the offshore supply operations. Such characteristics include the main dimensions, deadmass, capacity, maximum cargo deck, speed and power.

The operational model will be based on the consumption and supply of materials offshore. Such model requires information regarding the environment, the well to be drilled, the rig to be used, and the distance between the supply base and the drilling rig. The model then simulates the consumption and supply of the material to the rig and calculates the rig downtime, vessel utilisation, time vessels spend at sea and total fuel consumption.

The objectives of the economic model is to estimate the various costs associated with the supply operation. To achieve this aim, the model requires information on fleet characteristics, fuel consumption and rig downtime due to inadequacies in the supply operation. It can then be used to calculate the various costs attributable to the supply operation.

9.2.1 Types of Modelling

There are basically two types of modelling to be considered in studying offshore supply operations, that is, simulation modelling and direct modelling. *MacCallum* [4] describes simulation modelling as a technique which allows models of certain types of complex systems to be created and analysed by non-analytic techniques. Where probabilistic elements are built into the model, then the model needs to be run a large number of times, in order to build up statistical patterns of the results. Direct modelling entails using mathematical relationships to determine values for unknown parameters from a certain number of known parameters.

The type of model used in this study included aspects of both simulation and direct modelling. However, for simplicity, all the probabilistic elements were represented by typical values. This meant that the model need only be run once to obtain results, but the model would not give results on how fast the supply operation could respond to a random event.

9.2.2 Rules Governing the Supply Operation

In this study, it was decided to keep the model as simple as possible and at the same time as realistic as possible. Various rules will be incorporate in the model and discussed in following sections.

9.2.2.1 Rules for the Consumption of Materials

a. Only an operating rig will consume materials.

b. The rig will accept delivery of materials only up to its maximum variable deck load limits.

c. Requirements for equipment will be considered critical and will be assigned priority over all other requirements, or else the rig will cease drilling.

d. Rig will cease drilling if material requirements are not satisfied in time.

e. Rig may run out of supplies only while drilling.

9.2.2.2 Rules for Transportation of Supplies

a. The vessel will only transport what is ordered at the time it is at the shore base.

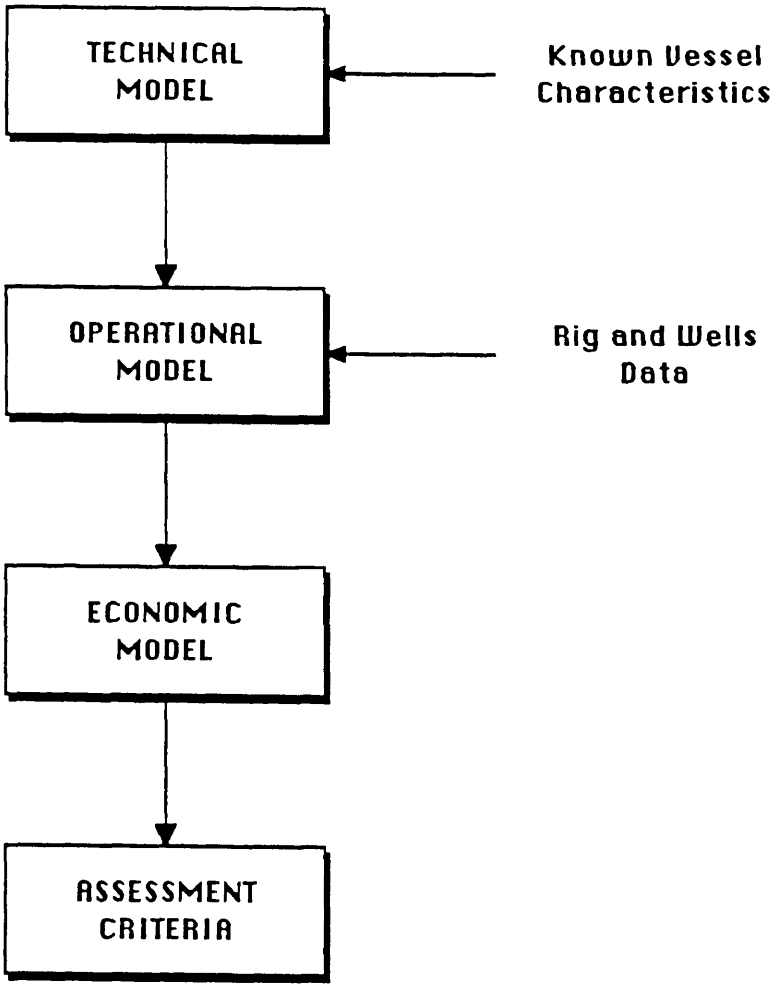

Fig. 9.3 Structure of the Overall Model

b. If no vessel arrives at the base on a certain day, then the order for that day will be added to the next days order (that is, the amount of material ordered by the rig in one day).

c. Any equipment order will be given priority over other orders and nothing will be loaded with the equipment.

d. The time spent discharging cargo at the rig will be increased to allow for extreme weather conditions.

e. The vessel speed will be modified for typical occurrences of sea state.

f. Vessel capacities are fixed and cannot be exceeded.

9.2.3 Model Mechanism

Basically, there are three mechanisms operating in the model. These are the consumption of materials, the transportation of the materials and updating the rig load.

For the consumption of the materials, the model takes account of the three main downhole consumables in the drilling of an offshore well (mud, casing, and cement). The casing is set when a certain depth of hole is reached and the cement is consumed directly after the casing as shown in Fig. 9.4. The amount of casing consumed is determined by the diameter of the casing and depth of the hole. The amount of cement consumed is determined by the annular space between the casing and the hole and the depth of the hole. The amount of mud consumed at any stage of drilling is very hard to predict and depends on many unknown variables including mud loss to porous rock, and increasing mud weight due to increase in pressure. The mud consumption for a typical well in the North Sea and the one used in this study are also shown in Fig. 9.4. The linear equivalent also shown in Fig. 9.4 is taken as satisfactory for mud supply.

The transportation of materials from the supply base to the rig involves a series of activities such as loading the materials onto the vessel, sailing to the rig, discharging the materials at the rig, and sailing back to the base. The first aspect of loading the materials onto the vessel is determining the load for the vessel. The first estimate for the load is based on the maximum amount of materials that will be loaded onto the vessel. However, if the storage space on the rig is less than the amount, then the vessel load will be reduced to the amount of the storage space available for it. Finally, if the

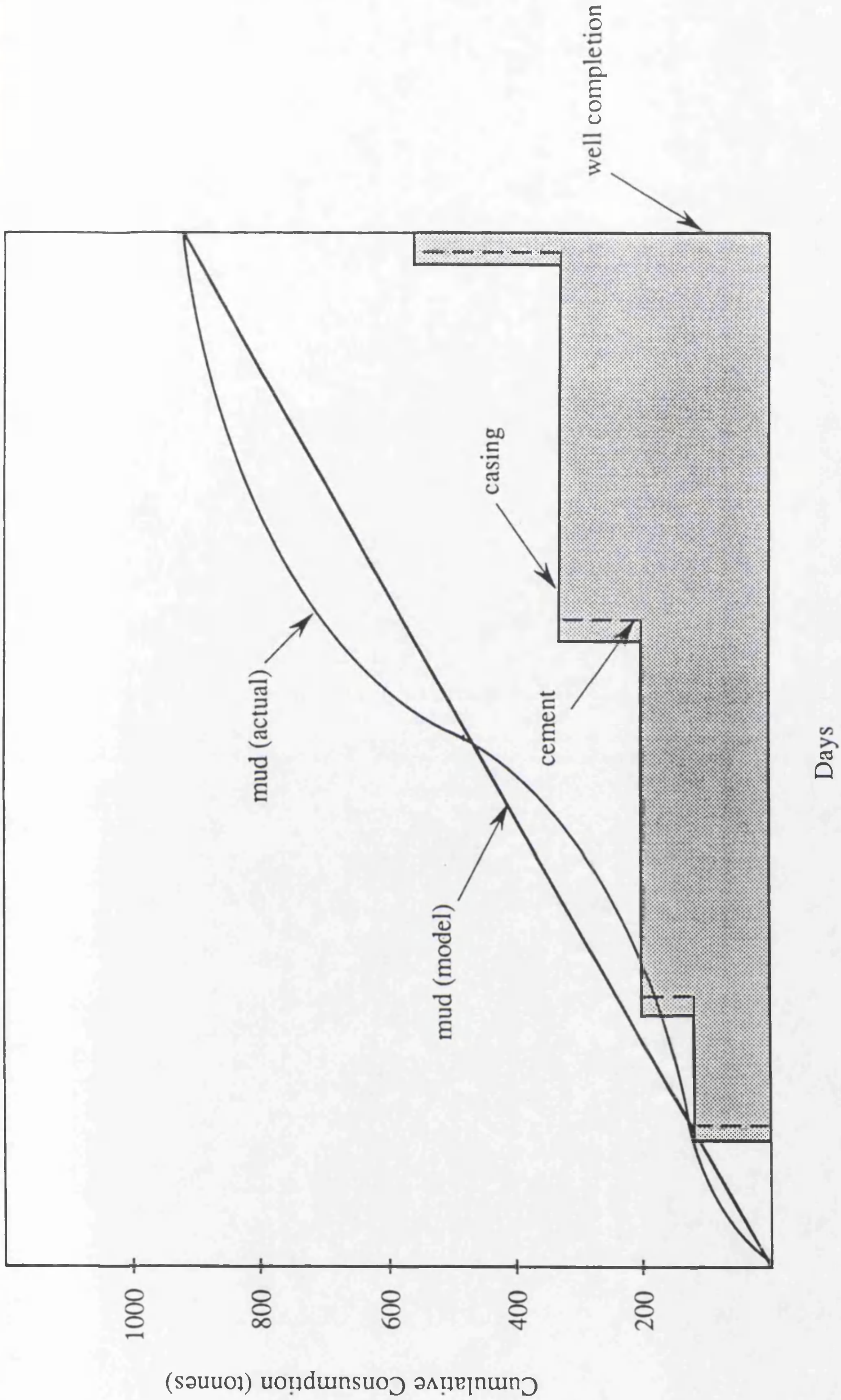

Fig. 9.4 Cumulative Consumption of Materials versus Time

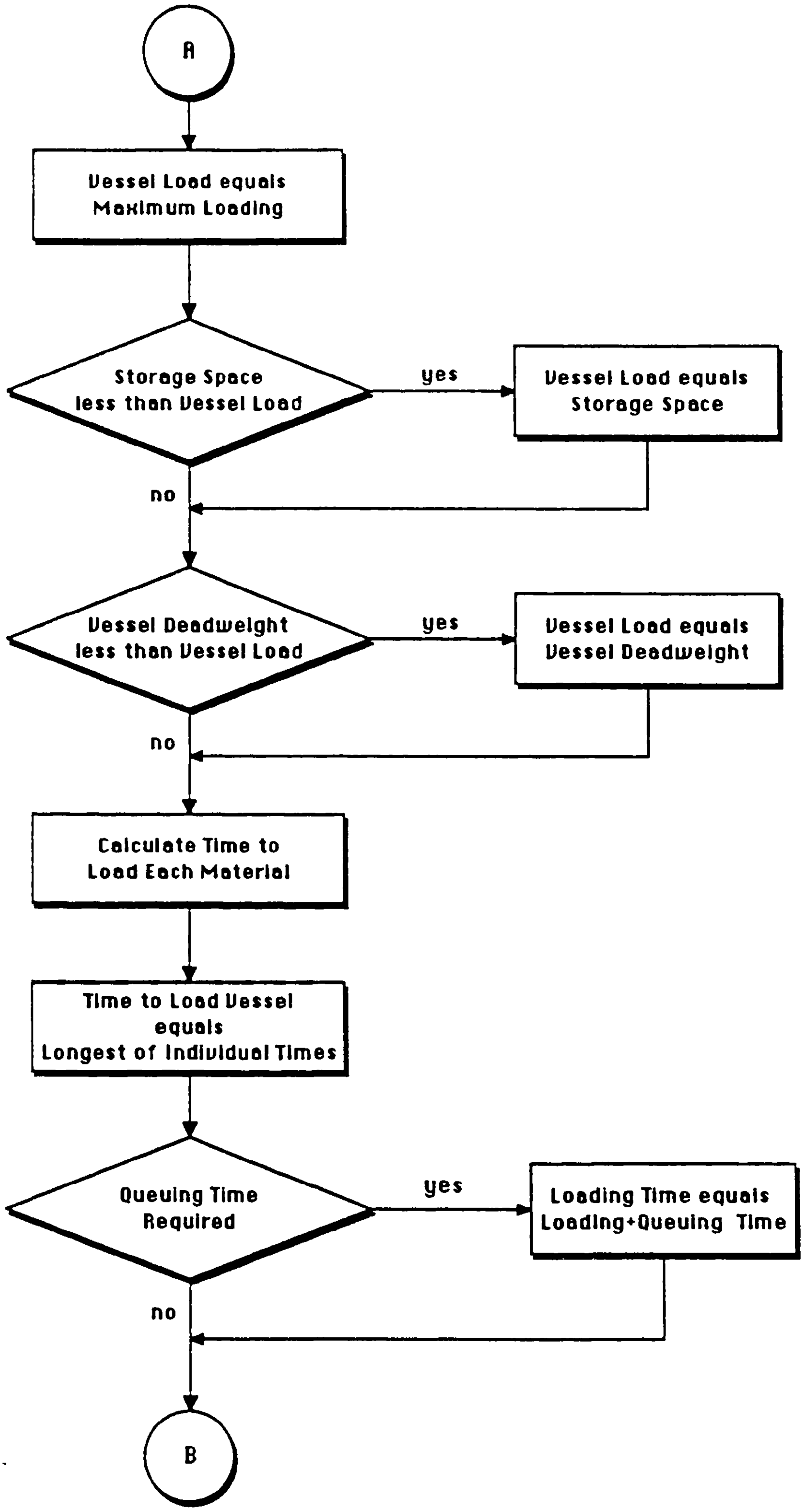

Fig. 9.5 Estimation of Vessel Load

vessel capacity is less than the load, then the vessel load will be reduce to the vessel capacity. This process is shown diagrammatically in Fig. 9.5. The length of time taken to load the vessel will be equal to the longest of the individual loading times for each material since the materials are loaded simultaneously. There may also be some extra time included for queuing at the base before loading.

The load on the rig is constantly changing due to the materials being consumed and more being supplied. Each time a vessel arrives at the rig, the amount of materials consumed since the last vessel arrives is subtracted from the rig load. The amount of materials supplied by the vessel is added to the rig load.

9.3 MAIN PROBLEM AREAS

The main problems associated with studying offshore supply operations is determining the effect that certain parameters have on such operations which include the environmental parameters, rig parameters, offshore supply vessel parameters, and economic parameters.

The environmental affects the supply operation in many ways as outlined in Fig. 9.6. These include loss of speed by the vessels due to seastate, loss of time in cargo

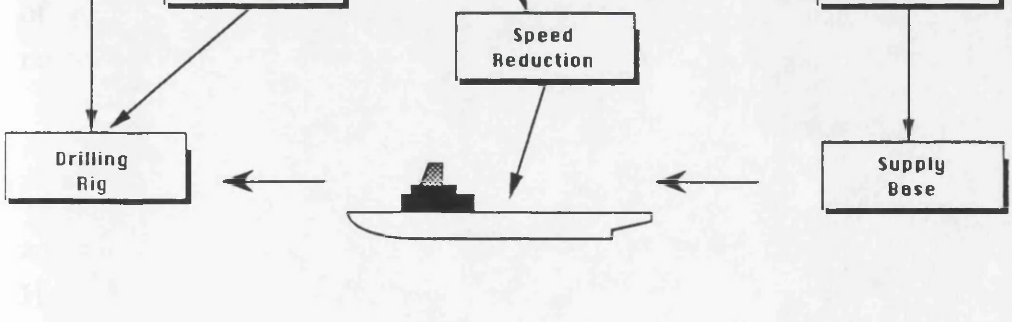

Fig. 9.6 Environmental Factors Affecting the Supply Operation

transfer due to excessive motion between vessel and rig and safety consideration. All these factors are random events and hence impossible to predict but must be included in the supply operation studies.

The main rig parameter affecting the supply operation is capacity. This dictates the amount of storage space on the rig at any given time. This storage facility on the rig allows the supply operation to build up a buffer storage by supplying more than what is being consumed in one period. If the rate of consumption increases, then this buffer storage prevents downtime on the rig, until it is used up. Then there will be downtime if the rate of consumption is greater than the rate of supply.

The effect of the offshore supply vessel characteristics is also difficult to predict. Using smaller vessels in the operation make it more flexible and increases utilisation of the vessels. Larger vessels will reduce operating costs since there will be less vessels needed, but lack of flexibility may increase downtime of the rig. Also, the large capacity of the vessel will be of little use if the rig cannot accept large amounts of supplies at any one time. This then will reduce the vessel utilisation (materials transported divided by transportation capacity). Thus, the important parameters of the offshore supply vessels are deadweight, bulk capacity, speed and fuel consumption rate.

The economic problem arises from the fact that different components of costs are important to the supply vessel operator and to the oil company. The supply vessel operator wants to keep the operating costs to minimum and hence increase his profit, while the oil company would like to reduce the costs incurred due to an inadequate supply operation to zero.

From this brief description, it can be observed that any decision making on the offshore supply vessel design, fleet dimensions and base location, for a given demand of supplies, is a complicated process. In addition to this, for a decision to have a rational basis, it must consider technological feasibility and economic viability.

At present, designing the offshore supply operation is usually a case of using two vessels to supply to a rig. Very little thought goes into evaluating capacities, speeds, and fuel consumptions, of different vessels in order to optimise the operation. However, offshore supply operations have now reached a point where oil companies are beginning to realise that the systems approach is needed for the selection of a suitable fleet size and capacity for any particular supply situation.

9.4 ASSUMPTIONS MADE IN MODELLING

All models have limitations on the degree to which they can represent a real life object or situation. These limitations are imposed by either the modelling technique or the difficulties involved in incorporating details. The degree of detail required is determined by the uses intended for the model. Once a certain level of detail has been decided upon, a number of assumptions need to be made to gloss over those details which are not significant.

9.4.1 Movements of Materials

The assumptions made with respect to the movements of materials include: the equipment orders are a fixed weight, base stocks are never exhausted, ordering of materials takes place a fixed amount of time before they are needed on the rig.

The model incorporates a fixed equipment weight of 100 tonnes. This fixed requirement acts as a reservation of deck capacity of the offshore supply vessel. The assumption that the base stocks are inexhaustable is a simplifying assumption which is justified on the basis that the model is not intended to investigate base operations.

For simplicity in modelling, a fixed preordering time is assumed for the reorder of casing and bulk materials. In reality this is not true since the dispatch of casing is considered a decision which relates to the progress of drilling operations. However, the assumption does not cause delays in the drilling operations.

9.4.2 Vessel Operations

In studying the operations of vessels, a large number of factors affecting them became apparent. While most of these factors have been included in the model, some have had to be neglected. The assumptions made to cover these areas are as follows :

a. The service speed of all the vessels has been assumed to be their speed at normal continuous service power.

b. No breakdown of vessels has been considered.

c. The different materials are loaded simultaneously.

d. The length of time to discharge materials at the rig is extended to take account of the probability of bad weather occurring which could interrupt or slow down the process.

e. Each vessel's voyage time is extended to take account of the prevailing seastate.

f. Vessel idle time is equal to zero.

While changes in speed caused by seastate conditions have been incorporated, no attention is paid to increasing speed, in an emergency, to the maximum speed. Vessel breakdowns have not been included. While this is not accurate, it was felt that the result of a vessel breakdown could be evaluated quite easily by studying the operation without the vessel that has broken down. This would allow the appraisal of situations resulting from a breakdown.

When an offshore supply vessel arrives at a rig , it may not discharge its load immediately due to bad weather or the preoccupation with other tasks by the rig personnel. However, for this model, it is assumed that the vessel begins unloading as soon as it is in location to begin discharging. The model assumes that each vessel is prevented from discharging its cargo for the percentage of time that the significant wave height to prevent cargo discharge is exceeded on average. In reality, some vessels may be prevented from discharging cargo for a long period and some may not suffer delays due to weather. Hence, the assumption is valid to use as an average figure.

The vessel voyage time is calculated taking into account occurrence of significant wave height. The values used are typical for the North Sea conditions. It is assumed that each voyage is affected in the same manner by these factors. This assumption was made for simplicity. The assumption that the vessel is never idle has the effect of increasing the percentage of the time of vessel spends partially loaded as sea. It was felt necessary to include this assumption in order to penalised an overdesigned system.

The overall structure of the operational model is shown in Fig. 9.7. Initially the day is set to zero. Then the first vessel load is calculated as described and the round trip time (time for the vessel to load, travel to rig, unload and return to base) is calculated. From this the time of arrival of a vessel to the rig is calculated. The day is then incremented by this period of arrival and the rig load is updated. Also, if there is any downtime, it is added to the total downtime. The fuel consumption for the voyage is also calculated and added to the total fuel consumption. If the material carried is less than the total material needed for drilling a well, then the next vessel load is calculated and the same process gone through until the total material carried is equal to the total material that is needed.

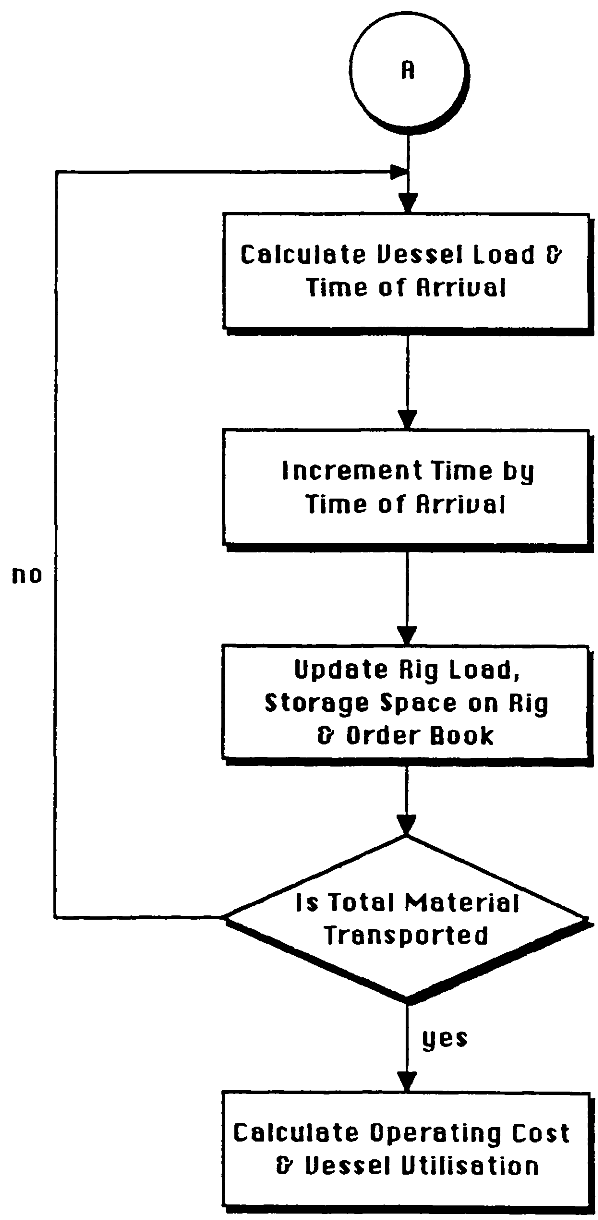

Fig. 9.7 Structure of the Operational Model

9.5 CRITERIA OF EVALUATION

Having described the supply operation in detail, the next aspect is to establish criteria for the evaluation of the operation and to propose a measure of merit. The possible measures that are relevant to evaluating the offshore supply operations are vessel utilisation and daily operating costs.

Vessel utilisation estimates the effective use which is being made of the offshore supply vessels for a given demand of supplies (total materials transported divided by the total transportation capacity). If utilisation is low, then the operation is overdesigned. However, if it is high, it could mean that the operation is underdesigned and hence would cause downtime on the rig. Hence it is difficult to say what the vessel utilisation should be for an optimum supply operation. However, it is still an important parameter to be included in any supply operation studies.

Through the operating costs of the offshore supply vessels, the estimation of the relative cost effectiveness of alternative supply operation designs can be evaluated. The main problem associated with the operating costs is to decide the minimum level of supply operation performance which is acceptable and how it could be specified. In this section, operating costs include the fuel costs, port charges and cargo handling costs.

Two other criteria that are examined are vessel sailing time and rig downtime. Vessel sailing time is defined as the total time sailed for the vessel to transport all the materials. It is used to compare the percentage of time the vessel spends sailing throughout the supply operation. Rig downtime assessment is important as any breakdown of supply will stop the drilling process.

9.6 CASE STUDY

The program is designed in such a way that enables a user to change any data regarding the loading and unloading rate of materials, the mud, cement and casing schedule, and the capacity of the drilling rig. A case study is done to conduct a general investigation of the capabilities of the model and the effects that various parameters have on the operating costs of the offshore supply operations.

The well to be drilled is an exploration well with a drilling depth of 3300 m and completed in 52 days. Other data are given in Table 9.3. Firstly, the effect of rig to base distance is look into. Figure 9.8 shows the effect of rig distance on the percentage

Table 9.3 Data for Case Study

Rig Maximum Loading		Loading Rate at Base		Discharge Rate at Rig	
Material	**tonnes**	**Material**	**tonnes/hr**	**Material**	**tonnes/hr**
Casing	400	Casing	40	Casing	30
Mud	350	Mud	80	Mud	60
Cement	300	Cement	80	Cement	60

of sailing time. From this plot, it can be observed that the sailing time can reach up to 90% of the total supply operation. Figure 9.9 shows the effect of rig distance on the utility of the vessel. The plot shows that the vessel utilisation increases steadily as the rig to base distance increases. Figure 9.10 shows the effect of rig distance on rig downtime. From the plot, it can be observed that the rig downtime increases with the rig to base distance and that this rate of increase depends on the vessel speed. For each speed there is a distance at which the rig downtime increases sharply and the distance at which this occurs increases with speed. Figure 9.11 shows the daily operating costs of the vessel against the distance of rig to base.

The next criteria to be analysed is the effect of deadmass of the vessel on vessel sailing time, vessel utilisation, rig downtime and the average daily operating rates and are shown in Figs. 9.12, 9.13, 9.14 and 9.15. As expected, increasing the deadmass of vessel would decrease the vessel sailing time, vessel utilisation and rig downtime, but would increase the daily operating rates.

9.7 CONCLUSION

The simulation model for offshore supply vessel operation developed in this study has been found to be very useful not only in estimating the operational costs but also useful in planning and evaluating the offshore supply system. The method developed comprises three basic components, that is, the technical, operational and economic models. The major part of this section entailed the development of the operational model which models the supply and consumption of materials. This resulted in many assumptions including using typical values to represent probabilistic elements.

The overall model developed allows the user to specify any of the data needed to use the program, but at the same time the program has built-in values of all the data required. Hence, unless the user specifies the data, the built-in data will be used. This allows the user to use the program and input only as much data as he wants. The method is not limited to offshore supply vessel studies but with some modifications could also be used for any type of ship operations including general cargo ships.

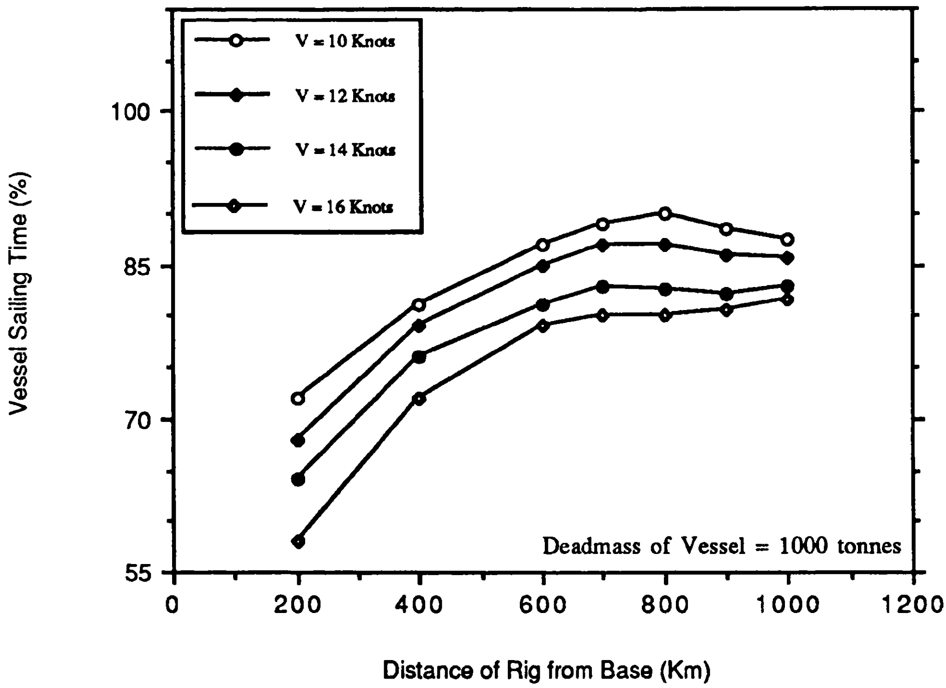

Fig. 9.8 Effect of Rig Distance on Sailing Time

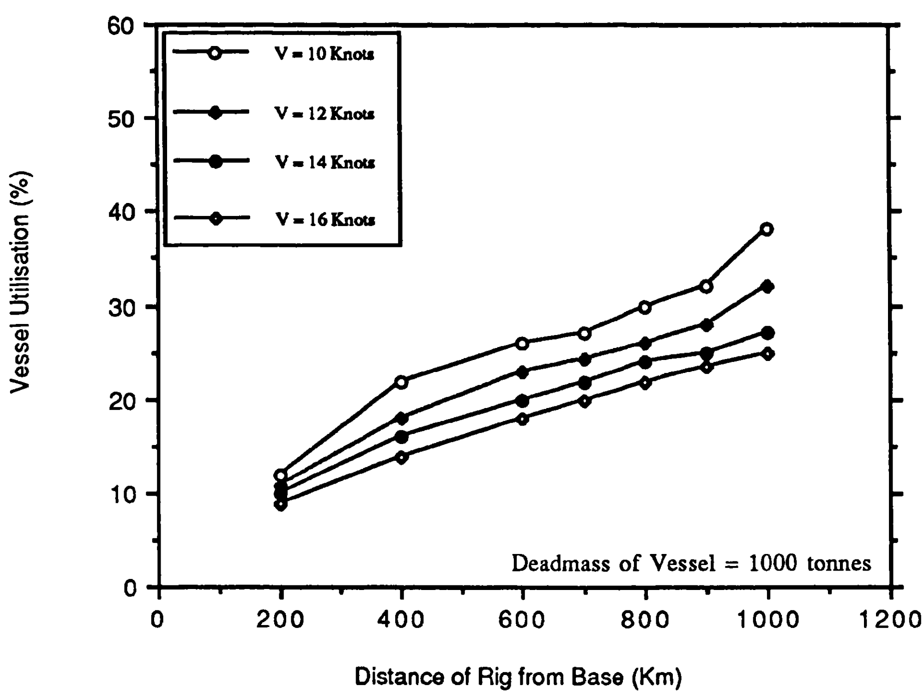

Fig. 9.9 Effect of Rig Distance on Utilisation of Vessel

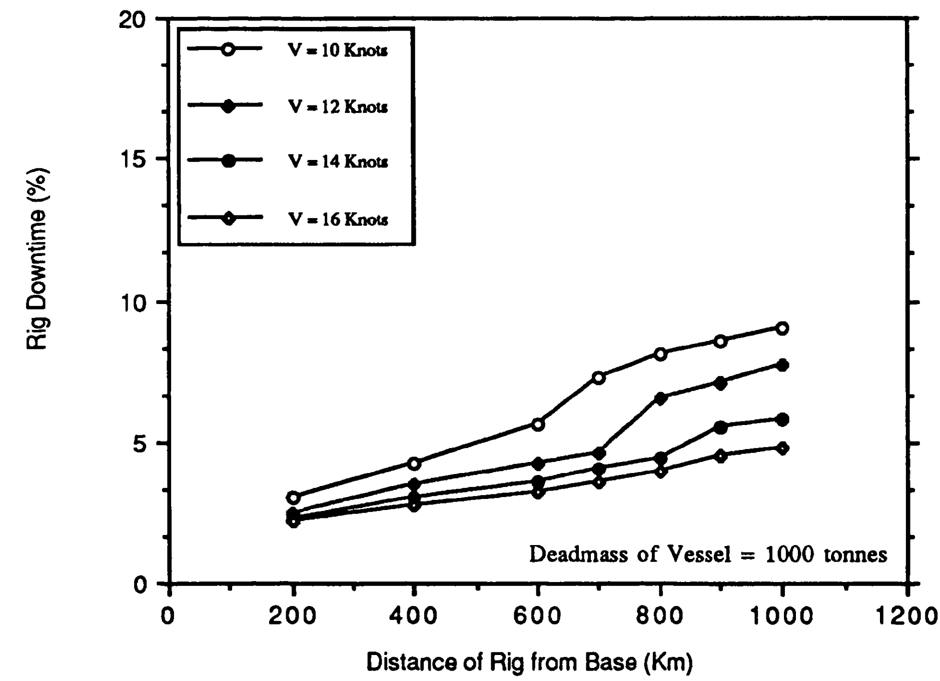

Fig. 9.10 Effect of Rig Distance on Rig Downtime

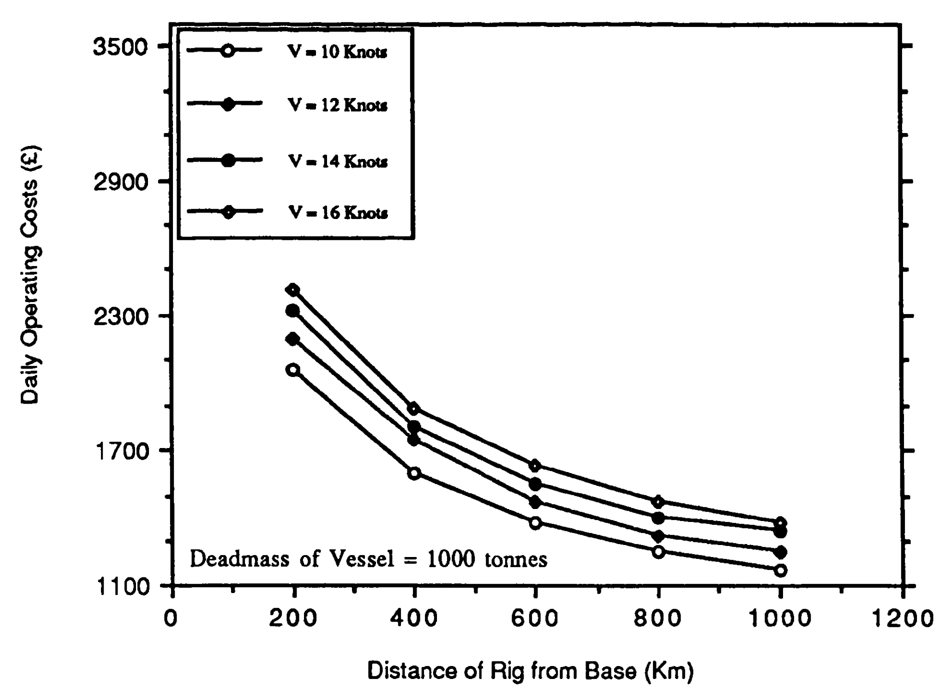

Fig. 9.11 Effect of Rig Distance on Daily Operating Costs

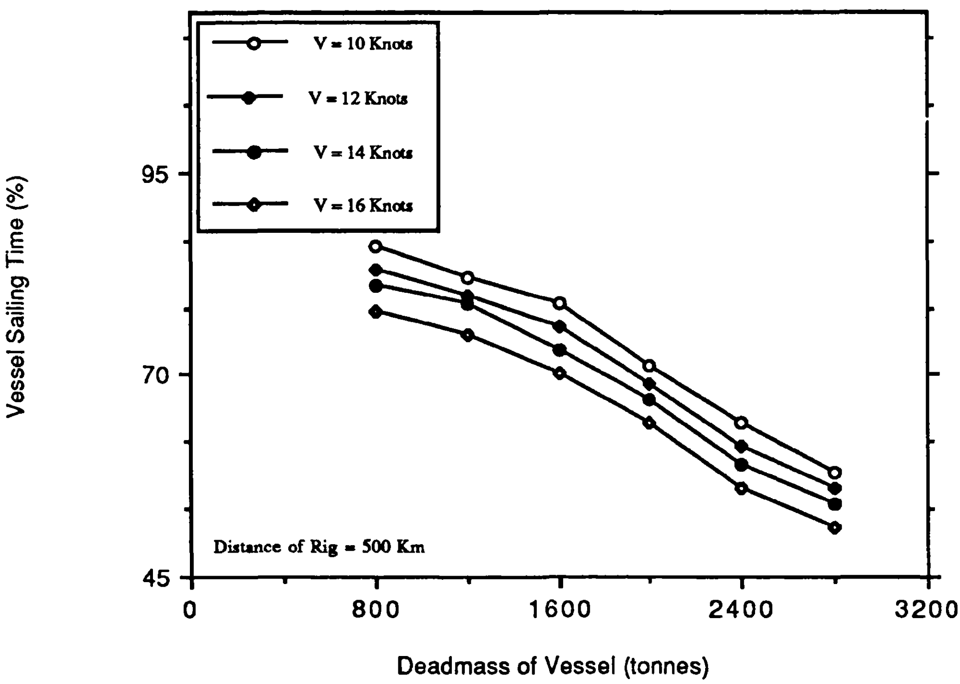

Fig. 9.12 Effect of Deadmass of Vessel on Sailing Time

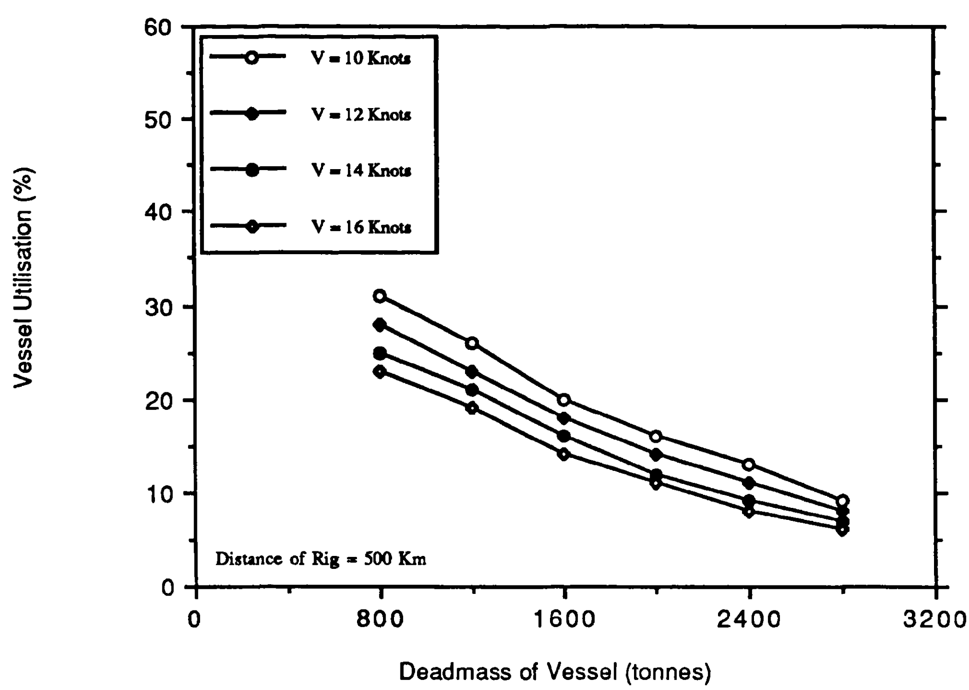

Fig. 9.13 Effect of Deadmass of Vessel on Utilisation of Vessel

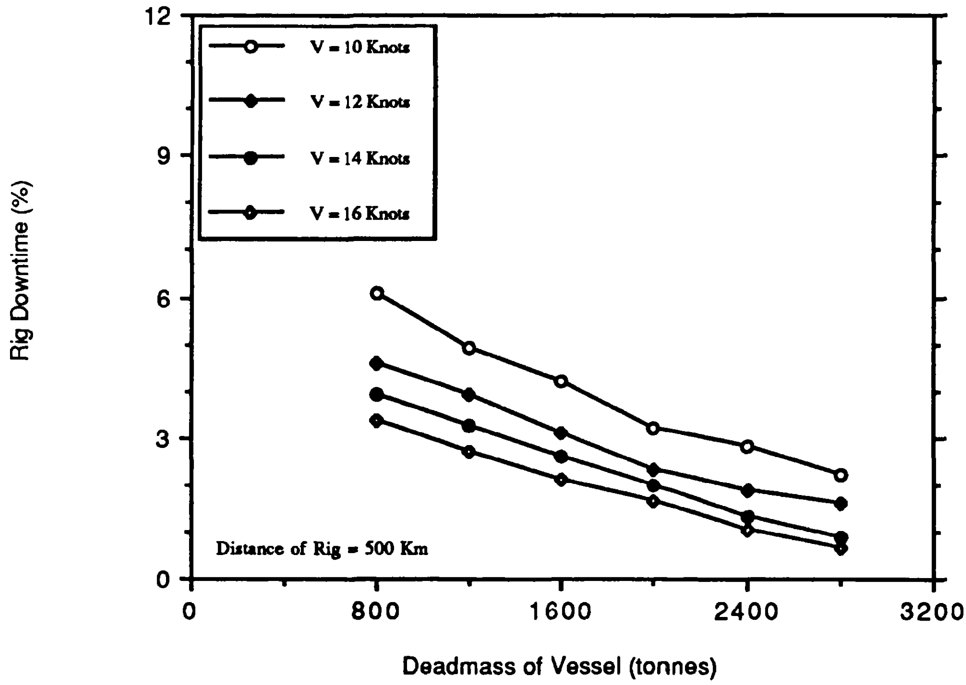

Fig. 9.14 Effect of Deadmass of Vessel on Rig Downtime

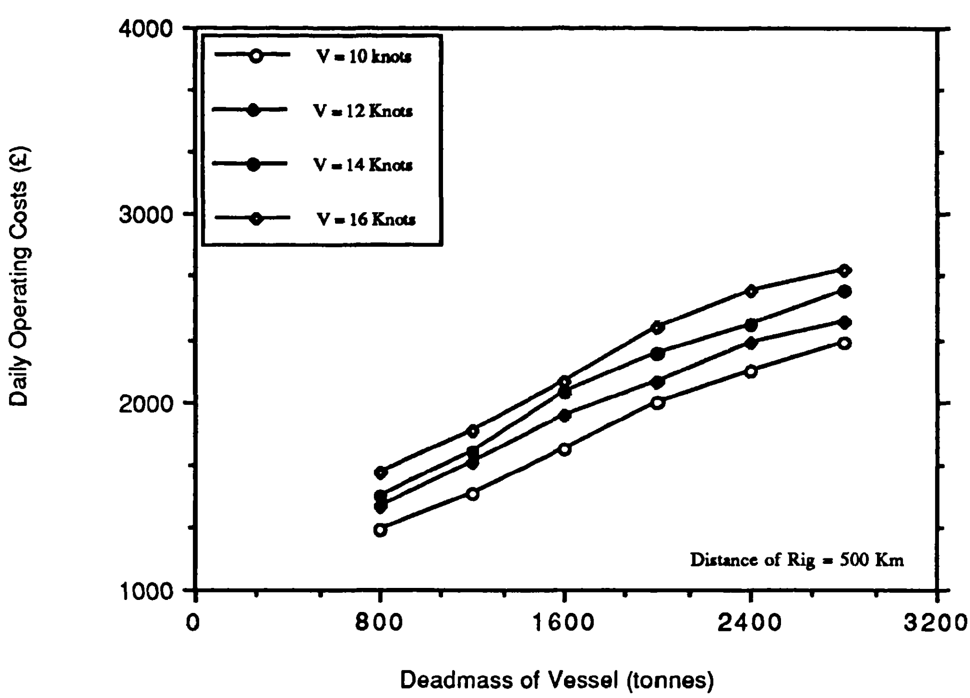

Fig. 9.15 Effect of Deadmass of Vessel on Daily Operating Costs

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CHAPTER 10

REVIEW OF THE APPLICATION OF COMPUTERS IN PRELIMINARY SHIP DESIGN

CHAPTER 10

REVIEW OF THE APPLICATION OF COMPUTERS IN PRELIMINARY SHIP DESIGN

10.0 INTRODUCTION

Ships are among the most complex and most costly engineering systems. Their design involves a wide range of technologies and the overall task of integration is correspondingly demanding. The difficulty of the task is exacerbated by the design requirements and constraints that are virtually unique to ship design. These include the hostile marine environment, and the need for a ship to be self supporting in that environment for up to months at a time. In addition, no prototypes are built, except in very rare circumstances, due to the high cost and small production runs evolved. Ships must work first time.

For decades ships have been designed using well-known 'basis ship approach' together with the equally well-known *Evans-Buxton-Andrews* spiral. Though, it has been quoted that the above approach has a number of limitations such as the process of design is assumed to be sequential and the opportunity to include life cycle considerations is limited, it will still remain popular and forms the foundation of any improvement in terms of efficiency and effectiveness of the process of ship design.

Since computers became the universal tool of engineers and scientists, dramatic changes had occurred in the computers themselves, the manner of using them, and in the opening of new related fields of research in science and technology. There are now computers that can process symbols in the broadest sense, words, graphs, and numbers, and they are imbued with the ability to reason. New software and hardware allow us to do things that, even a few years ago, we could contemplate only wishfully. Designers are on the threshold of being able to use a computer not just as a tool, but as an advisor, a critic and ultimately, as a partner in the process of design. The function of processing symbols in any design method is to provide a means for a designer to identify and formulate a problem so that it can be modelled as realistically as possible and to allow the formulation so generated to be translated into a structure amenable to solution.

From the earliest days of computer-based design, there has been a clear recognition that establishing effective communication between the computer and the designer is crucial to the development of a productive design system. Contrary to this, an examination of the developments in computer-based preliminary ship design leads to the conclusion that the greatest advances in the application of computers have been the assistance in 'number crunching' for design analysis, and the development of specialised systems for limited design tasks. Parallel improvements in man-machine communication have been achieved through improved availability and accessibility of computing power and significant advancement in computer graphics, providing a more acceptable medium for the exchange of information. However, even those advances have not made significant inroads into the problems of advanced communication.

Only recently, with increasing emphasis on product modelling, has there been a gradual awareness that the computer-based design systems require a much deeper level of user knowledge and problem knowledge than is currently normal. Therefore, it seems that much of the potential of computer-based design has yet to be realised.

This chapter will discuss the future development of computers to ship design, in particular, the preliminary stage of the design process. Before drawing any conclusions, a review of the ship design process and the development of computer-based preliminary ship design is considered.

10.1 NATURE OF THE ENGINEERING DESIGN PROCESS

In approaching and solving a problem, one of the initial challenges the designer faces is to understand the nature of the design process of the problem, the environment in which it exists, and the generating and response phenomena that are associated with the development of the problem and the impact of a proposed solution on this environment. A key characteristic of much of engineering design is the complexity of the objects or systems of interest. Typically, a system will have many components, each of which will be related in different ways to the other components through their characteristics. A designer's task is to create a specification for such a system, given a set of required functional objectives to be achieved in a given environment. The designer will rely on measures of performance, both objective and subjective, to select the most promising concepts for evaluation. Nevertheless, complexity prevents the designer from evaluating all concepts in detail; instead the design is broken down in parts and each part is tackled in a number of stages corresponding to levels of detail. Earlier stages have the least detail and use only the parameters which have the greatest influence on the overall design performance, whereas later stages operate within the constraint of previously defined parameters.

A conclusion which can be drawn from this brief description of the design process is that a designer's first expression of concepts are in term of objects, their characteristics and the relationships which exist among them. One way of viewing design is as a process of modelling in which the above expressions constitute the model. Thus in every situation, the designer creates some kind of abstract model which simulates some aspect of the behaviour of the object being designed. In fact, it is likely that for each concept, the designer handles a variety of models simultaneously, each one representing a different abstraction, but being consistent with the others. The models are essentially mental models but will be formalised through graphical, numerical, logical and physical means. The creation of a model, which is a process of synthesis, is difficult to formalise. Evaluation of a particular model, however, is a process of analysis. It requires effort and sometimes ingenuity, but in most cases the procedures of evaluation are well defined. The overall design process involves establishing and collecting a variety of models, interchanging synthesis and analysis, and allowing interaction between design objectives and model specifications.

In summary, it is useful to identify some important characteristics of the design process which includes :

a. *Creative* - It requires imagination and inventiveness to built models. As a result of creative activities, the form and structure of these models may change or develop as the design proceeds.

b. *Multiple Solutions* - There can be many answers to a given design problem, all of which may achieve the objectives, and may thus be technically and economically feasible. Thus, the design process is not deterministic. However, any design is a compromise representation of what is possible within certain constraints.

c. *Empirical* - The process of creating and evaluating a model does not always follow well formalised rules with good theoretical background. Very often relationships are of an empirical nature.

d. *Approximate* - Since design is a modelling process which uses empirical relationships, the results obtained are generally approximate. Accuracy increases as the design proceeds and greater levels of detail are included. However, the concepts of expected and acceptable accuracy are important to the designer.

e. *Requires Expertise* - The designer uses his expertise in many different ways during design, with respect to relationships used, the actual design process, and even in the judgement of the acceptability of proposed solutions.

f. *Measures of Merits* - In the process of addressing a design problem, designers may be required to assess the feasibility of a proposed design or evaluate alternatives that are under consideration. Basically, this involves an examination of costs, benefits, and consequences of the design or the alternatives over a period of time.

These characteristics are most in evidence at the creative or preliminary design stages during which the basic concepts are being developed. However, the same characteristics are the ones which in many circumstances are the most difficult to computerise, involving intuition, experience, approximation and empiricism. It is hardly surprising, therefore, that conventional approaches of computer-based design to the creative stage of design have had limited success.

10.2 NATURE OF THE SHIP DESIGN PROCESS AND ITS EVOLUTION

The ship design process closely follows the pattern described in the nature of engineering design. However, there is more architecture involved than in most engineering disciplines. The shape of the ship is important to its structural and hydrodynamic performance and to its aesthetic appeal, and the internal and external layout of the ship in both two and three dimensions is of major importance to successful design. Owing to the hostile environment, the need for mobility and the possible need to contain both fire and flood, a ship's layout is more heavily constrained by engineering and functional considerations than is the case in land based architecture. Human factors are of major concern too, not only in the operational and ergonomic sense but also due to ship motion effects. The successful designer will try to minimise the incidence of seasickness by careful attention to motion frequencies and to disposition of crew and passengers to positions of minimum motion amplitude.

In 1959, *Evans* [23] made a significant contribution to visualizing and modelling the process of ship design as shown in Fig. 10.1. Now known as the 'ship design spiral' it captured the basic tenets of a widely accepted approach to ship design. A major characteristic of the spiral approach is that the design process is sequential and

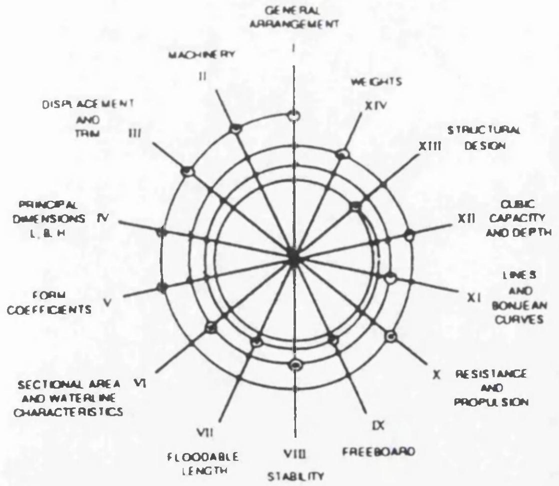

Fig. 10.1 General Design Diagram [23]

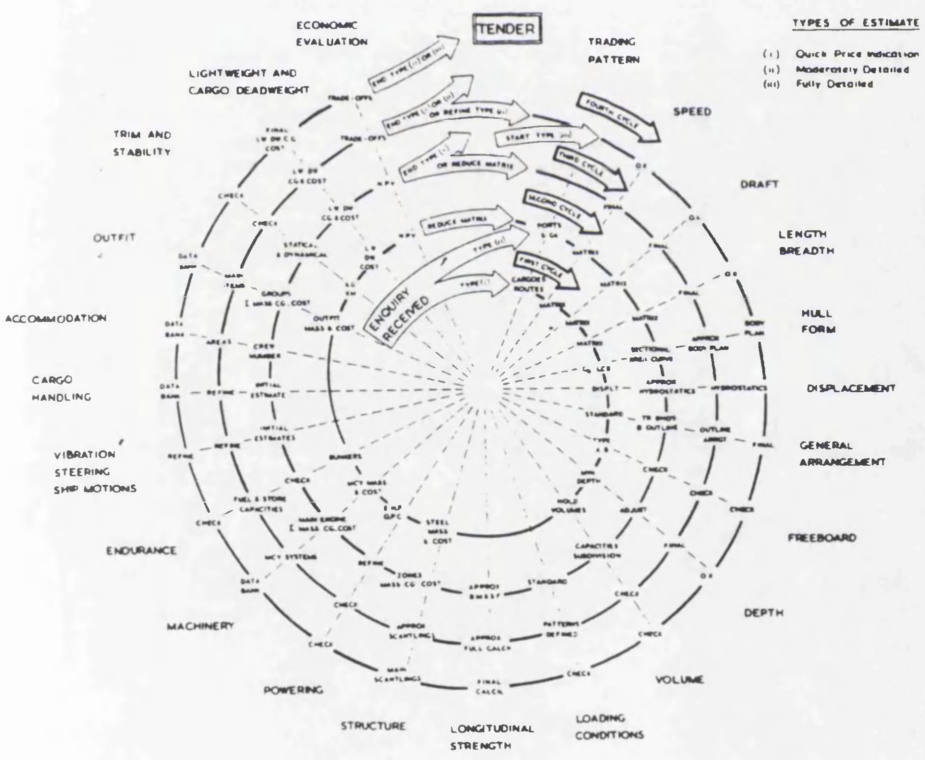

Fig. 10.2 Ship Design Spiral [1]

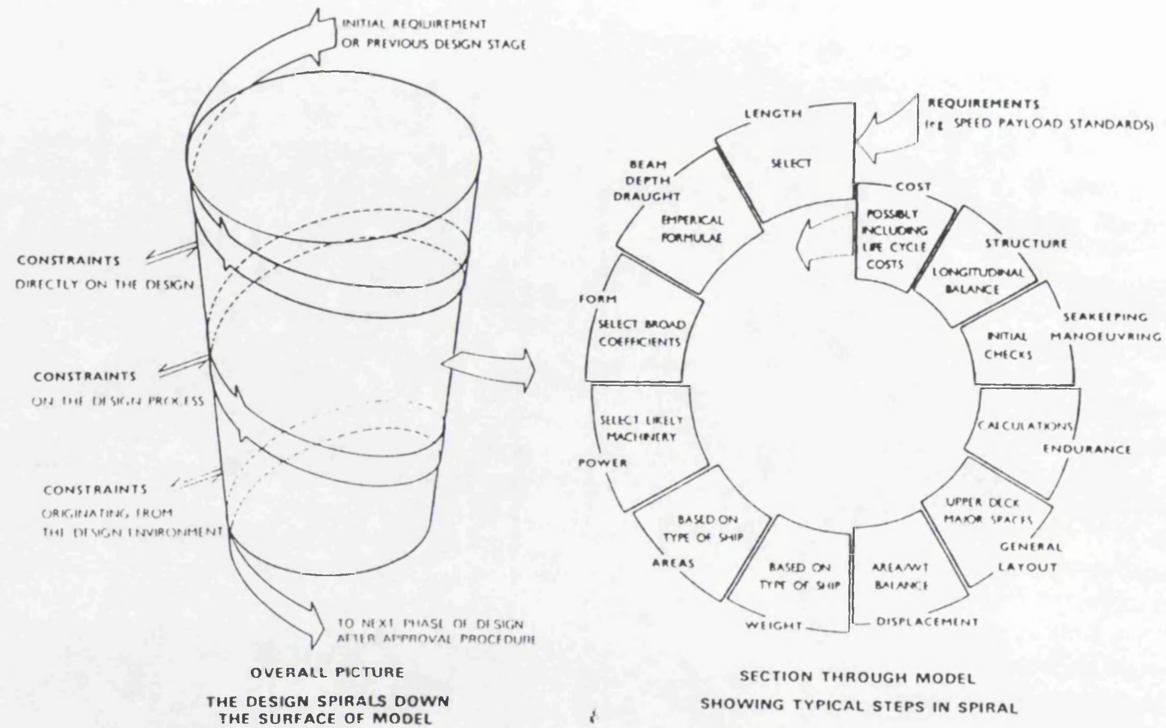

Fig. 10.3 Overall Model of Ship Design Process [24]

iterative. While some refinements have been made over time, these characteristics remain unchanged. *Buxton* introduced economic issue into the spiral [1] and time was added as a third dimension by *Andrews* [24]. In doing so, *Andrews* attempted to account for the open nature of the design process. Representation of the ship design process by *Andrews* as a helical 'corkscrew' is shown in Fig. 10.3 and he states that the advantage of this image is that many dialogues and constraints on a designer can be shown as fundamental to the design process.

It is widely recognised that the spiral represents an important historical model of the ship design process. Firstly, while the spiral is characteristically drawn by Evans and others as converging towards a product, the process is divergent with respect to information and the increasing detail of definition. This divergent aspect is reflected in Buxton's representation. The convergent/divergent perspectives of *Evans* and *Buxton* are complementary to each other. Secondly, it is recognised that when the spiral was formalised and in the years following, it represented a descriptive model that portrayed how design was done. It represented both the state-of-art (state-of-research) and the state-of-industry (state-of-practice).

According to *Lyon* and *Mistree* [25], even though the spiral approach may result in satisfactory designs, it does not promote the identification of superior solutions. They added that during periods when the shipbuilding industry is doing well and the volume of the shipbuilding is high, the traditional approach may be effective since :

a. the effort expended is worthwhile because almost all designs are built,

b. designs can be improved through small improvements from ship to ship and class to class, and

c. a large amount of data is available on similar ships.

However, when the market is depressed, with low ship construction activity, and in view of the specialised, single vessel designs encountered, the traditional approach is less effective since an adequate design may no longer be competitive in the open market.

The rapidity of calculation makes possible parametric studies in which a wide range of designs are generated. This ensure that almost all values of length, beam, depth and block coefficient can be located for a design. However is is more suited to show trends that are advantageous than to incorporate constraints for an individual design.

In conjunction with the above approach, another popular technique for preliminary ship design is the application of numerical optimisation methods for constrained and unconstrained problems. There have been a number of applications of such technique and each has had a varying degree of success. Different aspects of the preliminary ship design problem have been formulated and solve as single, objective, optimisation problems by *Mandel et al.* [18], *Nowacki et al.* [14], and *Kupras* [27]. The advantages of formulating a design problem as an optimisation problem are that computations are reduced, the computer code can generally be modified to accommodate the required number of design variables and constraints, and the 'best' solution as defined by the objective functions is found automatically.

In 1990, *Mistree at a*l. [26] proposed a contemporary paradigm, decision-based design, for the design of ships; one that encompasses systems thinking and embodies the concept of concurrent engineering design for the life cycle. Some principal observations from the decision-based design paradigm are as follows :

a. the principle role of a designer is to make decisions,

b. design involves a series of decisions ; some of which may be made sequentially and others that must be made concurrently,

c. design involves hierarchical decision making and the interaction between these decisions must be taken into account,

d. design productivity can be increased through the use of analysis, visualisation and synthesis in complimentary roles, and by augmenting the recognised capability of computers in processing numerical information to include the processing of symbols and reasoning,

e. life-cycle considerations that affect design can be modelled in early design decisions although the life cycle of one vessel is may need to be with one owner.

f. symbols are processed to support human decisions, for example, analog/digital signals, numeric information, graphic information, and textual information,

g. a technique that supports human decision -making, ideally, must be processed-based and discipline-independent, suitable for solving open problems that are characteristic of a fuzzy environment, and must facilitate self-learning.

Figures 10.4 to 10.7 some of the typical functions introduced in the new paradigm.

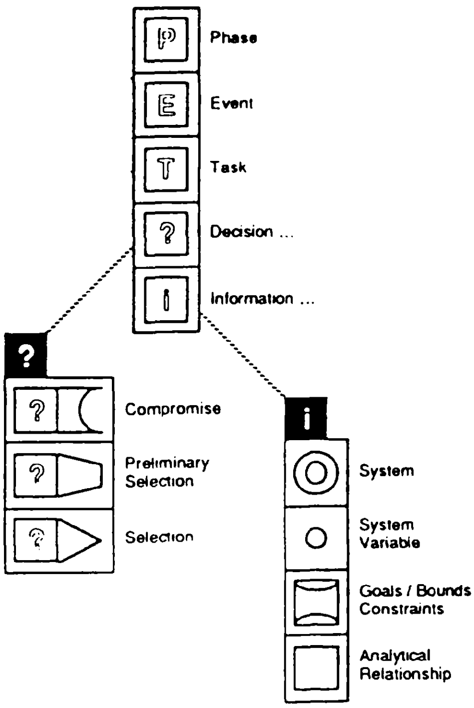

Fig. 10.4 Decision Support Problem Technique Palette for Modelling Processes [26]

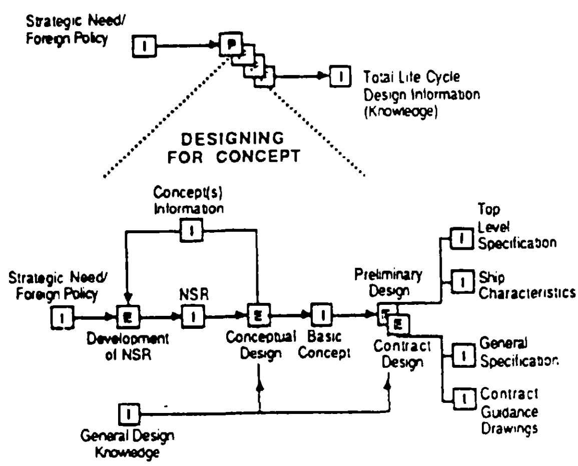

Fig. 10.5 The Designing for Concept Phase [26]

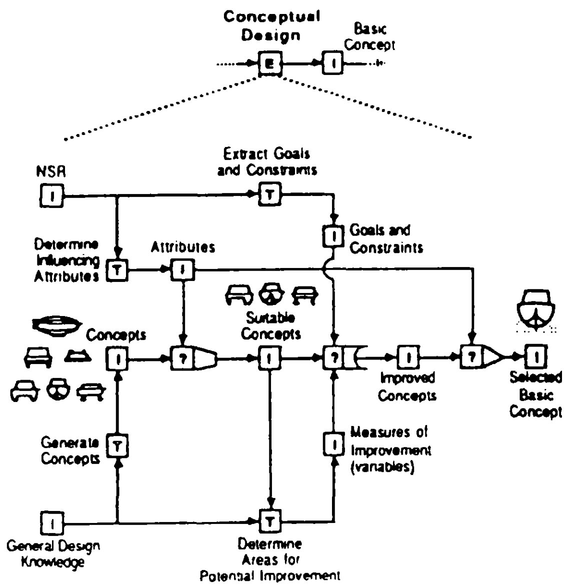

Fig. 10.6 The Conceptual Design Event [26]

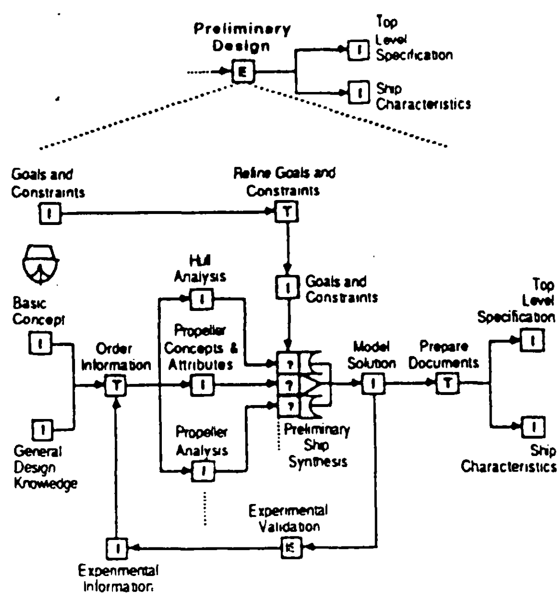

Fig. 10.7 The Preliminary Design Event [26]

10.3 MODELLING OF RELATIONSHIPS IN SHIP DESIGN

One of the most challenging problems for a designer is to be aware of and to understand the influence of one parameter or characteristic of the system on all the others. It could be said that if these influences are well understood, then it becomes easier to improve designs. However, it is possible to claim that this type of understanding is necessary for the creation of new concepts.

Relationships used in design may take many forms. Some of the most significant and frequently used are spatial, numerical, geometrical and social. Spatial relationships are used to describe arrangements and would include concepts such as 'next to', 'overlaps' and 'include'. The numerical relationships describe methods for applying numerical values to the characteristics of a design such as power, speed and mass. Geometric relationships include dimensions and relationship of space such as superstructure and double bottom tank. Finally, social relationships refer to living space arrangements, manning arrangement and consideration of safety. All these relationships will combine to influence the final design. At each stage of the design, relationships and their interactions are investigated by the creation of models of the design. In this sense, a model is an abstraction of the planned system which can be used to investigate and demonstrate certain aspects of the design. With the differing nature of the relationships, it is likely that it will include only those which assist the investigation. Thus, a number of different types of models may be required at each design stage.

In practice, the types of models commonly used in design are spatial and numerical. Spatial models today include drawings and two or three dimensional computer-based displays as well as physical models and provide the first picture of a design. Numerical models ensure that such a picture is feasible and will meet the performance criteria in engineering and economic terms.

To define and illustrate the role of the relationships in design process, it is valuable to have a more formalised way of presenting models and one way is to present a model as a directed network. In such network, the various nodes represent the characteristics of interest, and a link between two nodes represent a dependency as contained in some relationship, the direction of the dependency being shown by an arrow head as illustrate in Fig. 10.8.

A more realistic example which represents a simplified preliminary stage of ship design is shown in Fig. 10.9 [20]. As an example, ship length is shown as being dependent on displacement and speed, the relationship probably follows the Posdunine type. The steelmass of the ship depends on length, beam, depth and block coefficient (C_B) where the relationship follows the cubic number approach or one of the various other formulae developed for the steelmass calculation.

Several important points can be made in general about the approach of such modelling which include :

a. Some relationships are fixed in their form either because they follow physical laws or they are defined by legislative requirements while other design relationship are of an empirical nature. Thus, the results obtained by using such relationships can only be considered to be approximately correct.

b. Due to the empirical nature of the numerical design, a particular characteristics may have a number of valid relationships for estimating a value. The choice of which relationships to use in a particular instances will depend on particular contexts, degree of detail being considered, availability of other information and other expertise.

c. The inverse of the dependency network is an influence network. The effect of any characteristic on another can be determined by tracing through all the intermediate paths in the network.

d. Some relationships may need to be used in a number of different forms depending on the designer's approach to a problem.

In general, the directed network proves to be a useful method of modelling numerical design such as preliminary ship design in way of representing relationships. nevertheless, it rapidly becomes complex to visualise, and can only illustrate one network in detail within the total of networks.

10.4 COMPUTER APPLICATION IN SHIP DESIGN

The earliest application of computers in ship design were the tedious but already systematic calculations to determine hydrostatics stability and other similar characteristics of the hull form [15], [16]. The immediate success of these applications led to an early expectation that an extension of this approach to other ship characteristics would make it possible to explore many more alternative designs and thus select a more optimum solution. In addition, a much wider range of requirements could be considered and thus give greater confidence in the design.

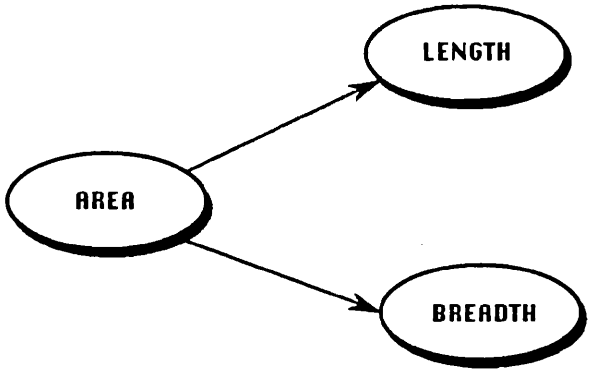

Fig. 10.8 Dependecy Network

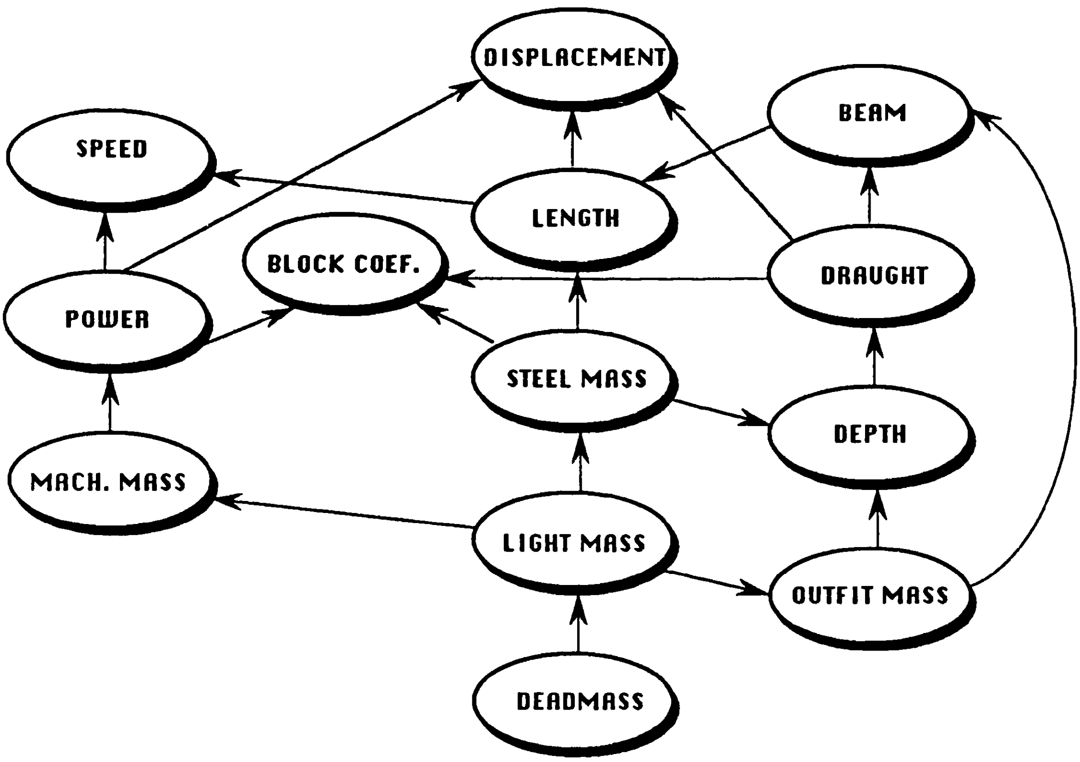

Fig. 10.9 Network for Preliminary Ship Design

In the last thirty years, the application of computers to ship design can be seen in two categories :

a. the development of independent programs based on advanced techniques to solve particular problems, and

b. the development of integrated design systems dealing with major sections of the ship design, using simplified analysis procedures.

Although the applications of computers have now been made in a wide variety of fields, only the progress achieved in preliminary design that will be considered here.

10.4.1 Computer Approach In Preliminary Ship Design

Development of large, free-standing programs for the preliminary stage of ship design has been a popular approach for computers [8], [10], [11], [13], [17]. Some of these have been formulated preliminary design as a mathematical optimisation problem in which the constraints and measures of merit are generally non-linear functions of the design variables [12], [14], [18], [19], [22].

Most of these programs have helped to demonstrate the potential value of computers for exploring generic alternatives. Some programs were before their time in computer terms but most have been valuable in forcing designers to try and understand this part of the design process more thoroughly and hence develop better design methods.

Some programs have been developed, either exclusively or primarily for the preliminary design of specific vessels. Such program are of interest partly because they have been developed by individual shipbuilding companies for their own use, but also because they contain some interesting technical estimating procedures, for example, for powering, steelmass, engine room length, and the arrangement of tanks for liquids and solids. Additionally, descriptions of these programs indicate that they include estimating procedures for the technical factors, building costs, operating costs plus economic evaluation routines which take into account different fiscal arrangement for funding, depreciation, and tax.

A number of criticisms can be levelled at the various approach of computer programs developed in respect of their success in assisting a designer with the preliminary design process which includes :

a. The expertise and knowledge built into the relationships, and their sequence of use is hidden from the designer within the program. Thus, a designer in such situation is tempted to accept results produced without question.

b. In most of the programs being developed, the user loses control over the design process. The user is restricted to the methods used by available programs and very limited facilities are given to the user to allow him to set up his own tests and evaluations.

c. Most of the programs produce results without increasing the understanding of the problem. Either a small number of 'best' solutions are produced, or in some cases, so much information is produced that a great deal of effort is required before useful solutions are isolated.

In general, most existing approaches to using computers for preliminary ship design have not been totally satisfactory. In particular, some of the programs lost the important features of design such as creativity and others do not tackle the important problem of assisting the designer to handle and understand relationships at the early stages of design.

10.5 CONCLUSION

The contribution of computers to the creative aspects of the design process has not been as great as might have been anticipated at one time. Computers should be used to build design tools which are available to the designer in a way which encourages him to create and describe new solutions, to explore and understand the solution spaces, and to move with confidence to the decision points.

From this viewpoint, the computer-based design approach should have methods of representation and reasoning which are closer to the designer's own methods of design experience and expertise. The present computer-based systems demonstrate very limited understanding of some of the most basic, general knowledge and conventions used by designers in their work, and that they have little explicit awareness of what a designer is trying to achieve. Both of these would seem to be fundamental if a system sets out to establish a higher level of 'interchange' with a user.

In short, a computer system for preliminary ship design should act as a design colleague and should have the following features :

a. a powerful semantic rich interface,

b. an 'understanding' of design goals,

c. a capability of abstraction,

d. a method of capturing and using expertise in a useful way, and

e. an ability to explain its own reasoning processes.

Further development is needed to achieve all these features in a system and the techniques and knowledge with which to construct it. However, the above list characterises the trend adopted by recent approaches to the problem.

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CHAPTER 11

INTRODUCTION TO EXPERT SYSTEMS

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11.0 INTRODUCTION

When computers were new and could do little except arithmetic functions, some called them giant brains, implying intelligence. Today, we do not regard the giant brain's successor, the pocket calculator, as intelligent. In fact, we do not regard a payroll program of hundreds or thousands of lines in code, running on a mainframe now orders of magnitude more powerful than its ancestors, as intelligent.

There are current systems, however, that we do regard as intelligent and expert systems are an example. They represents a new opportunity in computing technology. They open up avenues of application so far closed and allow new problems to be tackled. Although the ideas underpinning the technique are still in ferment, the techniques they employ have been in use for three decades or more. Nevertheless, it was only recently that they achieved prominence in the public eye and started to be exploited by commerce and industry.

The term *expert system* refers to a computer program that is largely a collection of heuristic rules (empirical rules) and detailed domain facts that have proven useful in solving the special problems of some technical field. Expert systems to date are an outgrowth of artificial intelligence, a field that has for many years been devoted to the study of problem-solving using heuristics, to the construction of symbolic representations of knowledge about the world, to the process of communicating in natural language, and to learn from experience. Expertise is often defined to be that body of knowledge that is acquired over many years of experience with a certain class of problems.

One of the hallmarks of an expert system is that it is constructed from the interaction of two very different people; a domain expert, a practising expert in some technical domain; and a knowledge engineer, an *Artificial Intelligence* specialist skilled in analysing an expert's problem-solving processes and encoding them in a computer system. The best human expertise is the result of years, perhaps decades, of practical experience, and the best expert system is one that has profited from contact (via the knowledge engineer) with a human expert.

11.1 EXPERT SYSTEMS VERSUS CONVENTIONAL PROGRAMS

An expert system is a program that relies on a body of knowledge to perform a somewhat difficult task usually performed only by a human expert. The principal power of an expert system is derived from the knowledge the system embodies rather than from search algorithms and specific reasoning methods. Such a system may also play the role of an assistant to a human decision maker. The decision maker may be an expert, in which case the program may assist by improving the decision maker's productivity. Alternatively, the human collaborator may be someone who is capable of achieving expert levels of performance given some technical assistance from the program.

Although more conventional programs have been known to perform similar tasks in similar domains, expert systems are sufficiently different from such programs to form a distinct and identifiable class. Thus, an expert system can be distinguished from a more conventional applications program in that :

a. It simulates human reasoning about a problem domain, rather than simulating the domain itself. This distinguishes expert systems from more similar programs that involve mathematical modelling. This is not to say that the program is a faithful psychological model of the expert, merely that the focus is upon emulating an expert's problem-solving abilities; that is, performing the relevant tasks as well as, or better than, the expert.

b. It performs reasoning over representations of human knowledge, in addition to doing numerical calculations or data retrieval. The knowledge in the program is normally expressed in some special-purpose language and kept separate from the code that performs the reasoning. These distinct program modules are referred to as the knowledge base and inference engine, respectively.

c. It solves problems by heuristic or approximate methods which, unlike algorithmic solutions, are not guaranteed to succeed. A heuristic method is essentially an empirical rule which encodes a piece of knowledge about how to solve problems in some domain. Such methods are approximate in the sense that they do not require perfect data and the solutions derived by the system may be proposed with varying degrees of certainty.

Although expert systems technology is derived from the research discipline of artificial intelligence (a branch of computer science concerned with the design and implementation of programs which are capable of emulating human cognitive skills such as problem solving, visual perception and language understanding), it differs from any other kinds of artificial intelligence program in that:

a. It deals with realistic and complex subject matter that normally requires a considerable amount of human expertise. Many artificial intelligence programs are really research vehicles, and many therefore focus on abstract mathematical problems or simplified versions of real problems to gain insights or refine techniques. Expert systems, on the other hand, solve problems of genuine scientific or commercial interest.

b. It must exhibit high performance in terms of speed and reliability in order to be a useful tool. An expert system must propose solutions in a reasonable time and be right most of the time or at least as often as a human expert.

c. It must be capable of explaining and justifying solutions or recommendations to convince the user that its reasoning is in fact correct. Research programs are typically run only by their creators, or by other personnel in similar circumstances. An expert system will be run by a wider range of users, and therefore be designed in such a manner that its workings are rather more transparent.

11.2 STRUCTURE OF AN EXPERT SYSTEM

A human expert uses knowledge and reasoning to arrive at conclusion. Likewise an expert system relies on knowledge and performs reasoning. The reasoning carried out in an expert system attempts to mimic human experts in combining pieces of knowledge. Thus, the structure of an expert system partially resembles how a human expert performs as shown in Fig. 11.1.

The first part of human expertise is a long term memory of facts, structures and rules that represents expert knowledge about the domains of expertise and this is analogous to knowledge-base in an expert system. The second part of human expertise

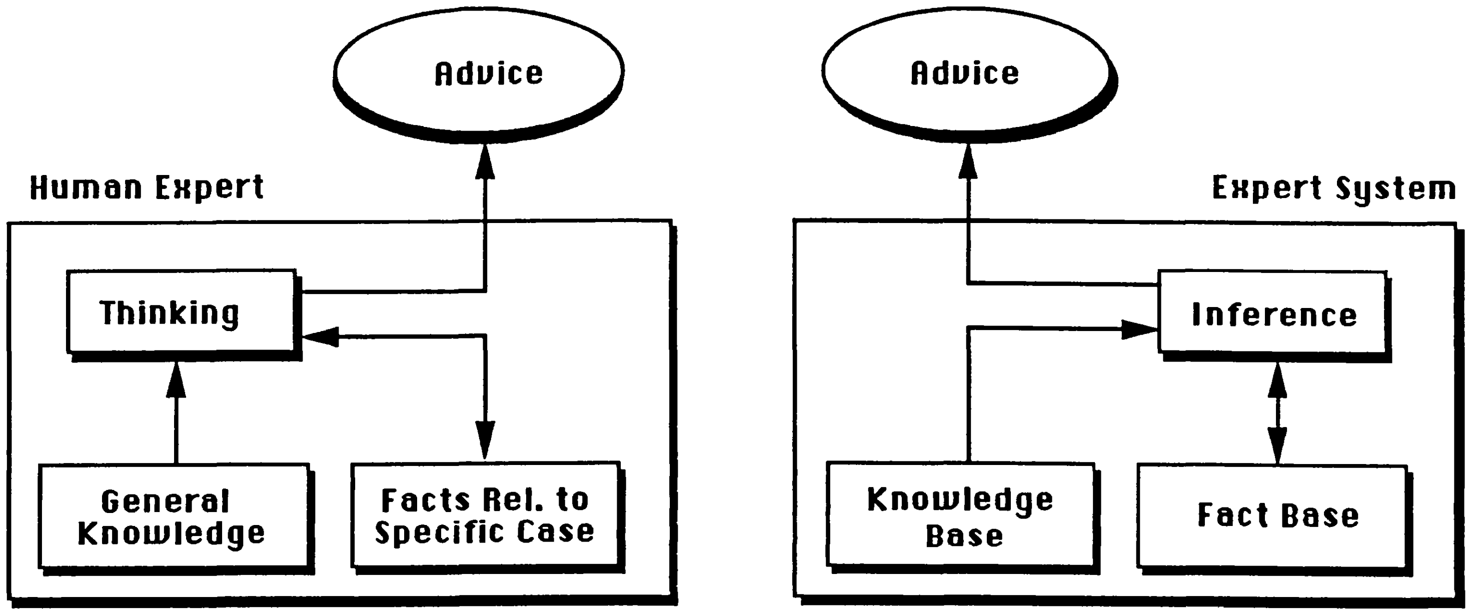


Fig. 11.1 Similarity Between Human Expert and Expert System

is a method of reasoning that can use an expert's knowledge to solve problems while an expert system carries out the reasoning function through the inference engine.

The knowledge within an expert system will include general problem solving knowledge as well as specific domain knowledge. The difference between the knowledge base and the inference engine parallels somewhat the distinction between general-purpose reasoning and domain-specific knowledge. In general, the domain knowledge is contained in the knowledge base. Usually, the general problem solving knowledge is built into the way the inference engine operates, thus enabling the same inference engine to be used in reasoning with different knowledge-bases.

Apart from the knowledge-base and inference engine, the expert system environment includes a number of tools for assisting people who build or use the expert system. When building an expert system, the developer uses expert system building tools to acquire, encode, and debug knowledge within the knowledge-base. Such tools include those for acquiring knowledge, knowledge-base editors, debuggers, compilers, and validation tools. Once the expert system has been developed, users utilise a variety of tools and interfaces to interact with the expert system. The expert system may be connected to real time data and external databases, or ~~to~~ be embedded in larger applications [3].

Just as human experts need a way of communicating with sources of information and with their clients to allow them to explore the particular details of a problem and to share their conclusions with clients, an expert system needs a user interface to allow users to query the system, supply information and receive advice. The user interface aims to provide the same form of communication facilities provided by the expert but often has much less capability for understanding natural language and general world knowledge. The user's impression of the expert system usually depends a great deal on the nature of the interface. The way in which the information is presented to the user should conform to the user's model of the task and expectation, which is generally referred to as cognitive compatibility. The fundamental idea of compatibility is that what users see conforms with concepts that are familiar to them and that the information is presented in a non-confusing and understandable way.

As human experts need to explain their recommendations or decisions, similarly expert systems too need to justify and explain their actions. The part of an expert system that provides explanation is called an explanation facility. The explanation facility not only satisfies a social need by assisting an end-user feeling more assured about the actions of the expert system but also serves as a technical assistance by helping the developer follow through the operation of the expert system.

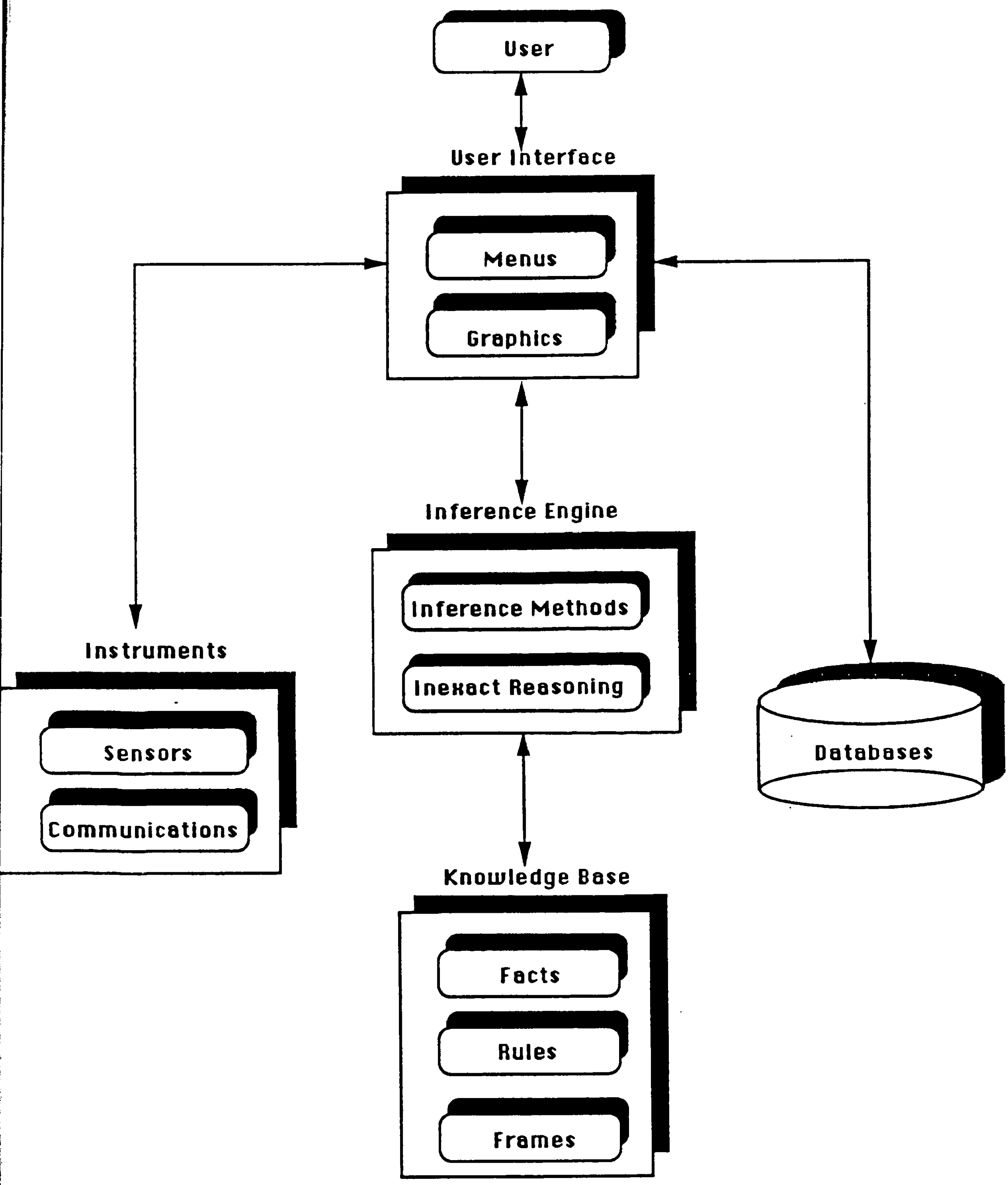


Fig. 11.2 Structure of an Expert System

Fig. 11.2 shows the basic structure of an expert system, which includes the user interface, knowledge base, an inference engine, and methods for building and updating the knowledge base.

11.3 STRUCTURING AND REPRESENTING KNOWLEDGE

Expert systems derive their power from knowledge. The heart of any expert system is the knowledge it contains, and it is the effective use of this knowledge that makes its reasoning successful. In order to represent knowledge in a machine, it must be possible to define the objective versions of knowledge for each domain of interest. Thus, the expert systems must deal with knowledge that has been structured and codified.

Expert systems employ knowledge to perform tasks that usually require a high level of reasoning ability in humans. To mimic the behaviour of a human expert, an expert system typically uses the same sort of knowledge as the expert. The knowledge used by an expert system needs to be presented and employed in a form that can be used for reasoning. This is in contrast to most computer programs that work with data. Thus, knowledge structures are used to store knowledge and reason with it, just as data structures are used to store and deal with data.

A good representation for structured knowledge should therefore have the following properties :

a. *Representation Adequacy* - It should support the acquisition of all the aspects of the knowledge in all their subletly.

b. *Representational Efficiency* - It should allow efficient acquisition so that the knowledge is stored compactly and is easily accessible.

c. *Inferential Adequacy* - It should be possible to use the knowledge in any way that may be appropriate.

d. *Inferential Efficiency* - The knowledge should be located and used rapidly and without the need of excessive computation.

Knowledge can be represented at different levels, depending on the degree to which fundamental principles and casual relationships are taken into account. In general, there are two types of knowledge levels, that is, shallow knowledge and deep knowledge. Shallow knowledge handles only surface level information that can be used to deal with specific situations. Deep knowledge, on the other hand, represents the internal and casual structure of a system and considers the interactions between its underlying components.

Shallow knowledge is concerned only with the type of information that is needed to solve a particular kind of problem, while deep knowledge can be applied to different tasks and situations. One way of viewing the distinction between shallow and deep knowledge is shown in Fig. 11.3. Although the system of interest represents a complex set of casual interactions, all that is represented in the shallow version of knowledge is the overall input-output behaviour of the system. For shallow knowledge, the internal structure of the system is hidden within a black box that cannot be opened and examined. However, deep knowledge takes the internal structure into account and tries to solve problems relying on the interactions between the fundamental components of a system.

11.3.1 Knowledge Representation Schemes

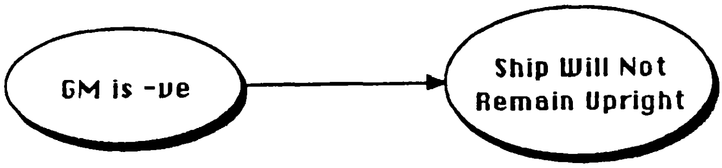
In practice, only a small number of schemes have been used to represent knowledge. The most common are :

a. *Rules* - Knowledge representation is, perhaps, usually associated with rules, but they do not necessarily always provide the most appropriate representation.

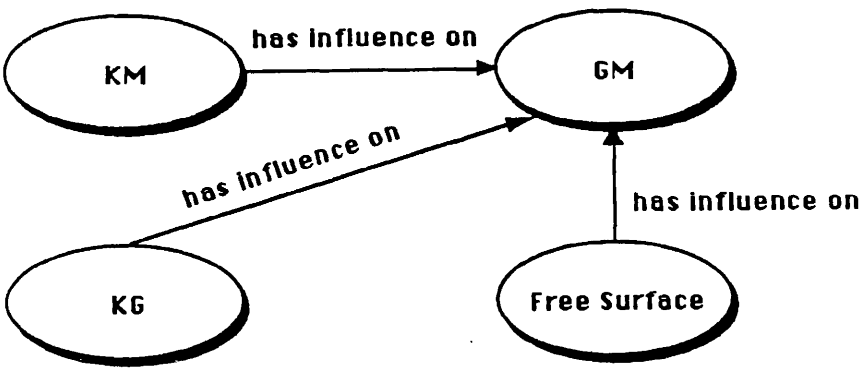
b. *Semantic Nets* - In providing a pictorial representation that is equivalent to a formal description, semantic nets can be easily appreciated.

c. *Logic* - Mathematical logic can be used as a formal language with the advantage that well-known mathematical techniques can be brought to bear.

d. *Frames* - This facility draws to some extent on the others.



Shallow Knowledge



Deep Knowledge

Fig. 11.3 Shallow and Deep Knowledge

11.3.1.1 *Rules*

Knowledge can be represented with rules of the general form :

IF condition **THEN** action

with a condition that, in specific circumstances, is either true or false, and an action to be carried out only when the condition is true. A rule could be written as :

IF condition - 1
AND condition - 2
AND condition - 3
THEN action - 1
AND action - 2

to indicate that only if all the conditions are satisfied should both actions be taken. A rule can also be written as:

IF condition - 1
OR condition - 2
OR condition - 3
THEN action - 1
AND action - 2

to indicate that all the actions should be taken if any one of the conditions is true. A rule of this kind is equivalent to a simpler set of rules, in this case to:

IF condition - 1
THEN action - 1
AND action - 2
IF condition - 2
THEN action - 1
AND action - 2
IF condition - 3
THEN action - 1
AND action - 2

To give an illustration of a rule from a typical rule-based expert system, an example is quoted below :

IF main_dimensions are obtained
AND weight_estimation is done
AND capacity_estimation is checked
THEN goal is obtained

It is possible to have rules that describe what to do with other rules, so introducing knowledge of a higher level. One way of doing this is to introduce a number of possible modes that the system may assume during its operation. Then rules such as :

IF condition
THEN action
AND mode is 2

can set the system to one of its modes. Other rules of the form :

IF mode is 3
AND condition - 1
THEN action - 1

only applies when the system is in a particular mode. A rule of the first kind has been used to decide which subset of rules of the second kind will subsequently applicable.

In short, it can be said that when knowledge is represented by rules :

a. 'chunks' of knowledge can be organised into modular form,

b. knowledge can be added to a knowledge base in a straightforward manner by adding rules to it,

c. rules about rules provide a way of supplying higher-level knowledge.

11.3.1.2 *Semantic Nets*

Semantic nets are well-suited for representing knowledge of a hierarchical nature. Figure 11.4 illustrates a representation of this kind for ship knowledge : the modes in the diagram represent objects and set of objects. The *is - an* label on an arc indicates that the object from which the arc originates is a member of the set to which the arc leads. An *AKO* (a kind of) link indicates that the set from which the arc originates is a sub-set of the set to which the arc leads. For this reason, an 'is - a' link is always found at the beginning of a chain of *AKO* links, as with the particular 'MASU PERDANA' which is an offshore supply vessel, which is a kind of service vessel, which is a kind of ship, and so on.

The net of Fig. 11.4 can be extended in the way illustrated by Fig. 11.5 to include properties of the objects represented by nodes. The arc label *has - property* denotes that the object from which the arc originates has the property to which the arc points. This figure serves to introduce the important idea of inheritance. As a particular vessel such as 'MASU PERDANA' is an instance of the class of all offshore supply vessels, it naturally has all the attributes of that class. The general attributes of an offshore supply vessel do not have to be attached to every instance of an offshore supply vessel, but can be inherited from class. This means that some of the attributes of a particular object can be found by moving up the *is -an* link from that object to the object representing its class and taking its attributes.

Another area where semantic nets are eminently suitable is in recording the way in which objects are made up of their component parts. The reason is, again, that the structure of knowledge is hierarchical. Fig. 11.6 shows the way that knowledge about how the displacement of a ship is composed of its various weights might be represented. The *is - part* link indicates both that an individual component is part of a sub-assembly and that a sub-assembly is part of the whole.

Fig. 11.7 demonstrates that attributes can be inherited from more than one chain of links. Clearly, the attributes inherited from one chain should not contradict those from another. It may be necessary to collect attributes from all the chains to get a complete description of the object, but in many cases a complete description may not be necessary. The real value of multiple chains of inheritance is that one of them may carry all the attributes that are needed in a particular case. In this way, the form of representation supported by semantic nets can give alternative perspectives on an object, each of which will be suitable at different times. By selecting the appropriate chain, an object can be placed in a given context with all the necessary properties.

11.3.1.3 *Logic*

Knowledge of an object can be represented by describing what is known to be true about it with correctly formed sentences of logic. Understanding the principles of logic is important for understanding expert systems. Further, logic may be viewed not only

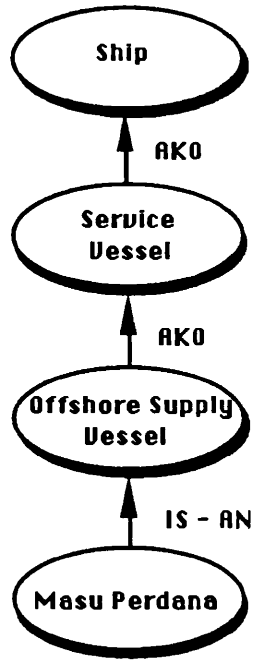


Fig. 11.4 A Simple Semantic Net

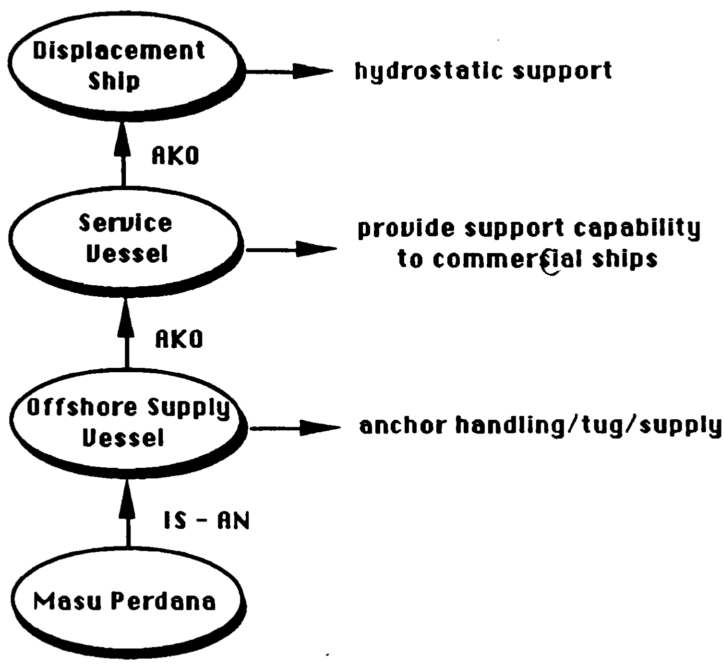


Fig. 11.5 An Elaboration of Simple Semantic Net

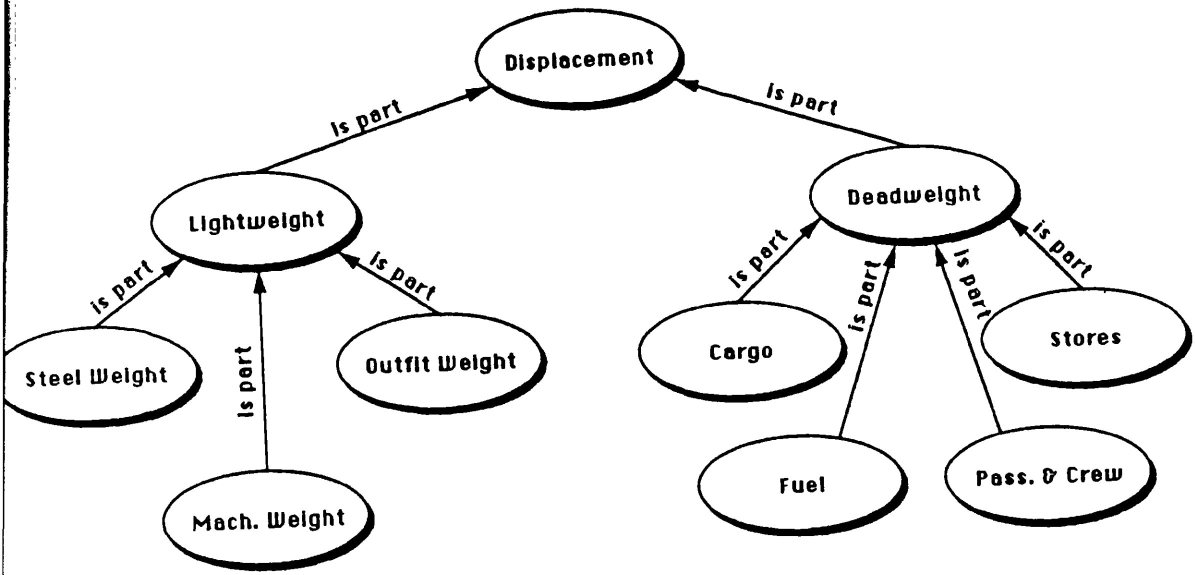


Fig. 11.6 A Semantic Net for Displacement of a Ship

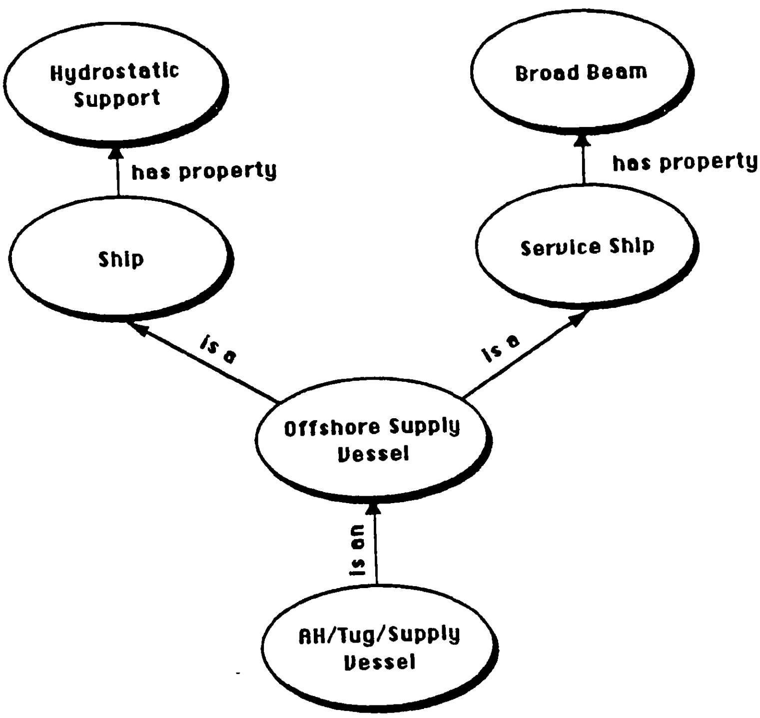


Fig. 11.7 Inheritance Via More than One Path

as a system of knowledge representation or inferencing but also as a high-level programming method.

There are many systems of logic, including propositional and predicate logic. Propositional logic is a simple and well known system that includes basic concepts such as truth values and logical connectives. Predicate logic is a more powerful form of logic which includes the notions of variables, quantifiers, and predicates. Predicate logic provides a precise and natural way of representing knowledge.

In logical knowledge representations, facts, knowledge and rules are represented in terms of predicates and logical sentences. Rules become readable and easy to understand when a suitable system for defining predicate logic is chosen. The essential idea behind formal logic is rather simple and is as follows:

a. There exist a number of statements that are assumed true (these are called axioms and facts),

b. There exist a set of general methods for combining some axioms to derive new conclusions (these are called inference methods),

c. The methods of inference are used to combined the axioms and obtain new facts.

The axioms describe the domain of interest in terms of logical structures that correspond to facts and rules. The rules of inference determine what can be inferred if certain axioms are assumed to be true. Thus logic consists of two basic steps, namely, representation and inference, which are analogous to the knowledge-base and inference engine of an expert system. Logics representation are operated on using the rules of logic to make inferences about the state of the world implied by logical assertions. Logic can be used to generate important, and not always immediately obvious, conclusions. Thus the type of reasoning that allows making somewhat hypothetical and academic statements can be used in more modern and practical settings. For instance, on the basis of the information :

Every supply vessel has broad beam and shallow draught.
MASU PERDANA is a supply vessel.

It might be deduced that

MASU PERDANA has a broad beam and shallow draught.

Formal logic allows things to be said precisely since it is based on formal definitions and methods of inference. The axioms here (which corresponds to knowledge) are :

MASU PERDANA is a supply vessel

IF 'X' is a supply vessel
THEN 'X' has broad beam and shallow draught

The rule of inference used above is that by knowing (A) and (If A Then B), then (B) is known. This rule of inference is usually referred to as syllogism.

Formal logic may be expressed in a large variety of notations. Despite the abundance of notation, logic is more palatable to most people if it is expressed in a way that conforms to the expectations that they have built up after years of using natural language.

11.3.1.4 *Frames*

As a means of representing knowledge, the frame is based on the observation that people do not construct their ideas about familiar objects, situations and events from scratch but carry with them a set of expectations about these things. Frames provide a method of combining declarations and procedures within a single knowledge representation environment. The fundamental organising principle underlying frame systems is the packaging of both data and procedures into knowledge structures.

Frames are organised into hierarchies or networks that can be used to inherit information, that is to retrieve properties that a lower concept shares with a whole class of concepts. In addition to organising knowledge in inheritance hierarchies, frames can also be linked to rules, allowing predicates to be activated when knowledge is stored and retrieved. The essential feature of a frame is that it contains slots that can be filled with values. Frames are essentially composed of their slots, just as record structures in a traditional programs are composed of fields. The basic components of knowledge are incorporated in frames as follows :

a. *Naming* - A unique name is assigned to each frame. A frame name may be any constant.

b. *Describing* - The body of a frame is composed of a number of slots or attributes that have values. These slots or attributes can be used to describe the properties of the frame or to link different frames together.

c. *Organising* - Each frame, except the top level frame in a hierarchy, has one or more parents, providing an inheritance mechanism.

d. *Relating* - The values of frame slots may be other frames. Frames may thus be related by having one frame as the value of a slot in another frame. Frames may also be related by rules.

e. *Constraining* - Each slot in a frame may have attached predicates, which are invoked whenever the slot is read or modified. Attached predicates include an if-needed predicate and an if-added predicate that is actuated when information is stored.

Fig. 11.8 shows typical examples of knowledge representation using frame.

11.3.2 Inference Process

The inference engine empowers an expert system with a reasoning mechanism and search control to solve problems. It can be either simple or complicated, depending on the structure of the knowledge base. For example, if the knowledge base consists of simple rules (that is no 'structured' rule set) and facts, a forward chaining may suffice. However, for a knowledge base that consist of structured frames and rules and unstructured logic (facts, data and variables), sophisticated forward and backward chaining with a well-planned search strategy may be required.

11.3.2.1 *Forward Chaining*

Forward chaining in its simplest form is an interactive program that performs a loop of substitution. It steps through the rule list until it finds a rule in which premises match

Name	: type_of_vessel
LongName	:
Type	: Text
Value	: pure_supply
Certainty	: {1.0}
DerivedFrom	: You input the value
DefaultValue	: pure_supply
FixedValue	:
AllowedValue	: pure_supply, anchorhandling_tug_supply
ForbidUnk	:
QueryPrompt	: What type of vessel do you intend to design?
QueryPreface	: In order to initiate the program, we need to know the type of vessel you intend to design. Please select by moving the cursor up or down and hit the <Enter> key.
Expansion	:
Commentary	:

Name	: STW
LongName	: steel weight evaluation
Type	: Procedure
AcceptsReal	: length, beam, depth, draught
AcceptsText	:
AcceptsList	:
ReturnsReal	: Steel_Weight
Returns Text	:
ReturnsList	:
LocalReal	: E
Local Text	:
LocalList	:
Body	:

```
/* Calculation of Steel Weight
   E = length * (beam + draught) + 0.85 *( length * depth - draught)
   Steel_Weight = 0.051 * (E^1.36)
   Return
```

Fig. 11.8 Example of a Frame Knowledge Representation the fact or situation. The rule will then be used or activated to assert a new fact. Once the rule has been used, it will not be used again in the same search; however, the fact concluded as a result of that rule's activation will be added to the knowledge base. This cycle of finding a matched rule, activating it, and adding conclusion to the knowledge base will be repeated until no more matched rules can be found.

Variations of the simple forward chaining form can be suggested to enrich the inference mechanism. The simple form can be enhanced in two ways :

1. by using a conflict resolution method (a tie-breaking procedure) to select one of the eligible rules when the premises of more than one rule match the fact, and

2. by considering the combination of conjunctive and disjunctive propositions in the premise or conclusion.

The first enhancement includes two features, that is, discarding those rules that would add only duplicates to the knowledge base, and executing a conflict resolution method to select one of the eligible rules. Combining conjunctive premises is discussed next in 'Backward Chaining' where the same principles can be applied in forward chaining.

11.3.2.2 *Backward Chaining*

Backward chaining reasoning is used when the user makes a query as to whether a certain fact is true and when there is a rule that can determine the query from known information in the knowledge base or from answers given by the user. In other words, backward chaining attempts to prove the hypothesis from facts. If the current goal is to determine the fact in the conclusion (hypothesis), then it is necessary to determine whether the premises match the situation. The example below will be discuss to show the logic of backward chaining.

Rule 1 :

> **IF** GM of vessel is less than 0.15 m and
> freeboard is less than 0.05 m
> **THEN** the design is a failure.

Rule 2:

IF the design is a failure and
you have no other alternatives
THEN you have to change the input data.

Fact 1 : GM of vessel is less than 0.15 m
Fact 2 : Freeboard is less than 0.05 m

For example, if the hypothesis 'you have to change the input data' has to be proven given the facts and rules in knowledge base (Facts 1 and 2, Rules 1 and 2), backward chaining can be applied to determine whether the premises match the situation. Rule 2, which contains the conclusion, would be activated first to determine whether the premises match the fact. because the knowledge base does not contain the facts in the premises of Rule 2, 'the design is a failure' and 'you have no other alternatives', 'the design is a failure' becomes the first subgoal, or subhypothesis. Rule 1 will then be activated to assert whether the premises 'GM of vessel is less than 0.15 m' and 'freeboard is less than 0.05 m' match the facts. Since the facts (Facts 1 and 2) in the knowledge base match the premise of Rule 1, the subhypothesis 'the design is a failure' is proven. However, the system still must prove the subgoal 'you have no other alternatives', which is not contained in the knowledge base and cannot be asserted through rules because no rule is related to it. The system will then ask the user "IS IT TRUE THAT : you have no other alternatives ?" If the answer is yes, then the second subgoal is also satisfied, and the original hypothesis is therefore proven, concluding that 'you have to change the input data'.

11.3.3 Search Strategy

There are three common search strategies used in expert system which are depth-first, breadth-first, and best-first. Each of the three strategies uses a slightly different approach to search for the target solution.

In a depth-first search, as illustrated in Fig. 11.9, the search starts from S down to A, B, and C. Only the left-most sub-node of each node is examined. If the node is not the desired node, the process goes down to the next level and chooses the left-most child of that node, always moving downward. If it reaches the bottom level without finding the desired choice, the process returns to the last node that contained a choice. Then the downward motion is repeated. For example, if the target node for the search

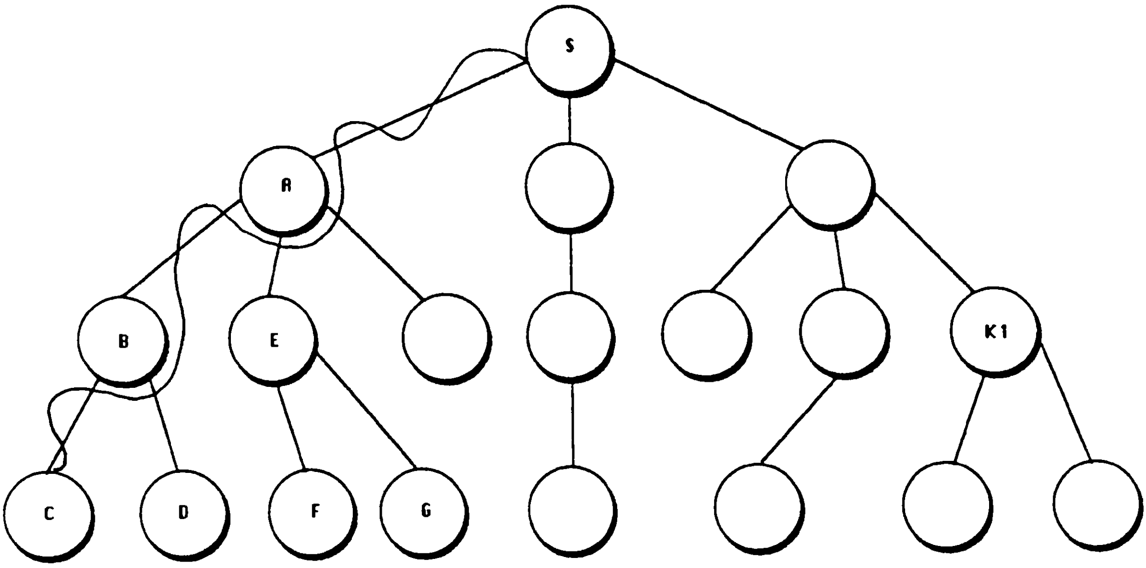


Fig. 11.9 Depth-First Search

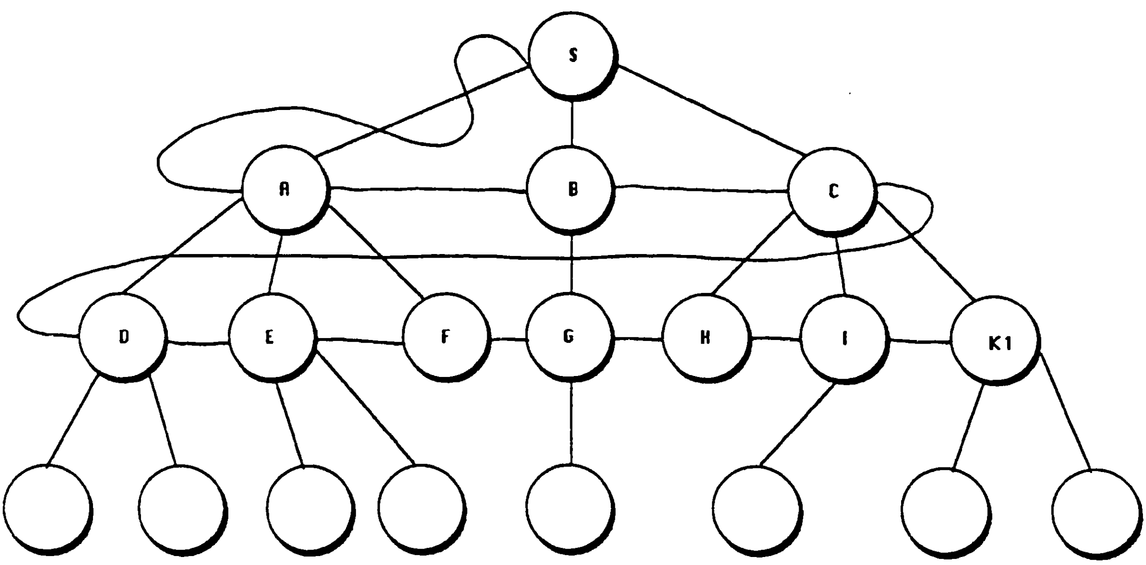


Fig. 11.10 Breadth-First Search

is K1 in Fig. 11.9, it will take a great effort for the depth-first strategy to reach the K1 node since the process has to go through almost all nodes before reaching K1.

In a breadth-first search, movement is performed level by level; the process examines all nodes on the same level one by one. If the target node is not found, then the process looks at those on the next level, as shown in Fig. 11.10. The same example of searching K1 is used to compare the difference in efficiency. Since K1 is on the third level, the search process will need to examine only 10 nodes to reach K1, in comparison with 16 nodes in the depth-first search. Whether the breadth-first search is more efficient than the depth-first search depends on where the target node is. Consequently, it sometimes pays to make a good guess about how far the target node is from the current node and select the shortest path leading to the target node. This strategy is known as the best-first search.

The two elements required in a best-first search are complete ordering of the paths, and a method to determine the reasoning distance between the current node and the target node.

11.4 DEALING WITH UNCERTAINTIES

The need for systems that can deal with knowledge that is uncertain and incomplete is part of the reason for the existence of expert systems. In situations where observations produce definite results and there is no doubt which procedures are needed to process those results, expert systems are usually not needed because conventional programs are adequate. Coping with uncertainty in reasoning is a complex area within the field of artificial intelligence. As with other issues, the techniques actually used for uncertain reasoning in expert systems are only a subset of a large class of methods that may be considered.

There are two general ways in which uncertainty may be dealt with in an expert system. One aspect of uncertainty stems from the incompleteness of information, that is, it is not that the information is inherently uncertain, it's just that the information is not available. The other aspect of uncertainty arises in those cases where the knowledge itself is inherently imprecise. Many expert systems assume that the knowledge base is fairly complete and that any symptoms of incompleteness should be debugged and rectified. Thus the treatment of uncertainty in expert systems has often focused on the problem of imprecise information. The mechanism for transforming uncertainty into certainty is of course the collection of pertinent facts that confirm the hypotheses, hunches, or whatever that were initially generated by some type of uncertain reasoning.

Several methods have been proposed for dealing with uncertain information during inferencing in expert systems, which include probabilities, fuzzy logic, and certainty theory. However, while there are a number of definitions of uncertainty, the issue of how to use uncertainty in an expert system is quite another matter. A major obstacle is how does one specify just how uncertain is a piece of knowledge.

Once what uncertainties to attach to knowledge within the knowledge base is clear, focus can then be concentrated upon taking the uncertainties into account during inference. It should be clear, though, that the quality of uncertain reasoning will depend to a great extent on how well the basic uncertainties are qualified, as well as methods for combining uncertainties during inference.

11.4.1 Probability Theory

The mathematical theory of probability provides a means of dealing with knowledge about truly random events. One of the component of probability theory which is widely used in expert systems is Bayes' rule which provides a way of computing the probability of a hypothesis being true given some evidence to that hypothesis. Before stating Bayes' rule, some useful terminology is introduced such as:

a. $p(E/H_i)$is the probability that evidence E will be observed given that hypothesis Hi is true.

b. $p(H_i)$ is the 'a priori' probability that H_i is true. That is, based on past experience, $p(H_i)$ is simply the probability that H_i is true irrespective of any evidence for or against it in some particular case.

c. k is the number of possible hypotheses which display evidence E.

Given these definitions, Bayes' rule states that the probability that hypothesis H_i is true given evidence E (which is denoted by $p(H_i/E)$) may be calculated as follows:

$$p(H_i / E) = \frac{p(E / H_i) * p(H_i)}{\sum_{n=k}^{n=1} p(E / H_n) * p(H_n)} \qquad \text{Eqn. 11.1}$$

Bayes' rule may be expressed in a different form, as follows :

$$\phi(H_i / E) = LS * \phi(H_i) \qquad \text{Eqn. 11.2}$$

where

a. ϕ stands for 'odds' and is related to probability as follows:

$$\phi(x) = \frac{p(x)}{1.0 - p(x)} \qquad \text{Eqn. 11.3}$$

$$p(x) = \frac{\phi(x)}{1.0 + \phi(x)} \qquad \text{Eqn. 11.4}$$

b. LS stands for 'likelihood ratio' and is calculated as follows:

$$LS = \frac{p(E / H_i)}{p(E / \neg H_i)} \qquad \text{Eqn. 11.5}$$

where $p(E/\neg H_i)$ is the probability that E is displayed when hypothesis H_i is false.

The LS value indicates the extent to which the presence of E to support the validity of the hypothesis H_i. Complementary equations may also be written for the case in which E is absent (denoted by $\neg$ E). The equations are:

$$\phi(H_i / \neg E) = LN * \phi(H_i) \qquad \text{Eqn. 11.6}$$

where

$$LN = \frac{p(\neg E / H_i)}{p(\neg E / \neg H_i)} \qquad \text{Eqn. 11.7}$$

The LN value indicates the extent to which the absence of the evidence E supports the non-validity of the hypothesis H_i.

11.4.2 Fuzzy Logic

Fuzzy logic, derived from possibility theory, is used to deal with vagueness as distinct from randomness. If P is a set and e is a member of P, then a fuzzy subset F of P can be defined by introducing a membership function @F such that @F(e) = d where d is the degree to which e is a member of F. For example, if P is the 'set of all type of ships' and F is the 'set of large ships', then @F can be defined as follows:

@F(supertanker) = 1.00
@F(containership) = 0.80
@F(bulk carrier) = 0.60
@F(supply vessel) = 0.20
@F(speed boat) = 0.05

A fuzzy statement such as 'a large ship' is interpreted as having an imprecise denotation characterised by a fuzzy set. A fuzzy variable Y is a variable which can take values in P as well as values 'assigned' to it by statements such as :
'Y is an F'

If effect, the value of Y is a possibility distribution such that the possibility that Y = e is @F(e). For example, the statement

'Y is a large ship'

signifies that the possibility that 'Y = supertanker' is 1.0, the possibility that 'Y = supply vessel' is 0.2, and so on.

11.4.3 Certainty Theory

This theory was developed for use in expert system with an attempt to overcome the problems associated with probability theory. In this theory, a 'certainty measure' C(S) is associated with every 'factual' statement P such that :

a. C(P) = 1.0 if P is known to be true

b. C(P) = -1.0 if P is known to be false

c. C(P) = 0.0 if nothing is known about P

d. Intermediate values indicate a measure of certainty or uncertainty of P.

Knowledge which shows how factual statements are related is represented as a set of rules such as :

IF P1 **THEN** P2 with certainty factor 0.6

IF P2 and P3 **THEN** P4 with certainty factor 0.3

The 'certainty factors' associated with rules are measures of reliability of those values. In general, rules are written with the following format :

IF A **THEN** X with certainty factor CF

where A is called the condition part and X the conclusion. If the condition part of a rule is true, that is if it has a certainty value of 1.0, then that rule can be used to compute a new certainty value for its conclusion as follows :

a. If C(X) and CF are both greater than 0.0 then the new certainty of X, denoted by C(X/A), is computed according to the following equation :

$$C(X/A) = C(X) + [CF * [1.0 - C(X)]] \qquad \text{Eqn. 11.8}$$

If the certainty value C(X) of a statement is positive, then the most that a rule with positive CF can increase the certainty of X is 1.0 - C(X). This amount is multiplied by CF and added to C(X).

b. If C(X) and CF are both less than 0.0, then the new certainty of X is computed according to the following equation :

$$C(X/A) = C(X) + [CF * [1.0 + C(X)]] \qquad \text{Eqn. 11.9}$$

c. If C(X) and CF are opposite sign, then the new certainty of X is computed to the following equation :

$$C(X / A) = \frac{C(X) + CF}{1.0 - \text{min. of } \{|C(X)|, |CF|\}} \qquad \text{Eqn. 11.10}$$

where $|\alpha|$ is equal to α if α is positive, and $-\alpha$ if α is negative.

In some cases the condition part of a rule R will be uncertain. That is, C(A) will be less than 1.0. Such cases can arise for two reasons :

a. A might be evidence which is empirically uncertain

b. A might be a conclusion of another rule

In either case, the certainty of the conclusion of R must be reduced accordingly. One approach is to multiply the certainty factor of the rule by the certainty of the condition if this certainty is positive, and to ignore the rule if the certainty is negative. Another approach is to require that the certainty of the condition be above some threshold before the rule may be used.

For rules having complex conditions such as the following examples :

IF [A AND B] **THEN** X with CF1
IF [A OR B] **THEN** Y with CF2
IF [A AND NOT B] **THEN** Z with CF3

The certainty values of the complex conditions can be computed using results from the theory of fuzzy sets :

a. the certainty of [A AND B] = minimum of {C(A), C(B)},

b. the certainty of [A OR B] = minimum of {C(A), C(B)},

c. the certainty of [NOT A] = 1.0 - C(A)

Suppose the following rules exists :

R1 : if A then X with certainty factor 0.8
R2 : if B then X with certainty factor 0.5
R3 : if [X AND E] then Y with certainty factor 0.8

Suppose also that observations made such that C(A) = 1.0, C(B) = 1.0, and C(E) = 1.0, and that the initial certainty values of X and Y are both 0.0. The revised certainties of X and Y can be calculated as follows :

(a) Using R1:

$$C(X/A) = 0.0 + [0.8 * [1.0 - 0.0]]$$
$$= 0.8$$

Thus C(X) is now 0.8

(b) Using R2:

$$C(X/B) = 0.8 + [0.5 * [1.0 - 0.8]]$$
$$= 0.9$$

Thus C(X) is now 0.9

(c) The certainty of [X AND E] = minimum of {C(X), C(E)}
= 0.9

Hence the modified certainty factor for R3 is 0.8 * 0.9 = 0.72

(d) Using R3:

$$C(Y/[X \text{ AND } E]) = 0.0 + [0.72 * [1.0 - 0.0]]$$
$$= 0.72$$

Hence the revised certainty of Y is 0.72.

11.5 EXPERT SYSTEM TOOLS

The majority of software tools for building expert systems seem to fall into five broad categories :

a. *Expert System Shell* - A domain-independent expert systems framework, that is, an inference engine with explanation facilities, but without any domain specific knowledge.

b. *High-level Programming Language* - Languages such as LISP and PROLOG, which to some extent conceal their implementation details, thereby freeing the programmer from low-level considerations of efficiency in the storage, access and manipulation of data.

c. *Multiple-paradigm Programming Environments* - Sometimes called hybrid systems, which provide a set of software modules that allow the user to mix a number of different styles of artificial intelligence programming.

d. *Skeletal Systems* - Systems which provide the knowledge engineer with a basic problem-solving program to be initiated.

e. *Additional Modules* - Modules for performing specific tasks within a problem solving architecture.

11.6 EXPERT SYSTEM LIMITATIONS AND DIFFICULTIES

The limitations of expert system development may originate from technology, inheritance, environment, and cost. Since current expert system technology is still evolving, limitations include the inherent shortcomings, such as narrowness of expertise, inability to recognise knowledge boundaries, limited explanation facilities, and difficulty in validation.

As building and maintaining a large knowledge base requires substantial effort, most expert systems covers a narrow range of expertise. Part of the reason is due to the current computing facilities, which limits the speed and capability of searches in expert systems. Even when an expert system achieves a broad coverage of knowledge, it becomes shallow in representing associations between elements in the knowledge base. Inability of expert systems to recognise their knowledge boundaries is a serious problem since most expert systems do not deal competently with problems at the boundaries of their knowledge. They do not have the built-in knowledge to determine when a problem is beyond their capability or outside their field.

Although validation of software programs is time-consuming, the effort required in validating expert systems is many times greater than the effort required for conventional software programs. The environment in which an expert system is developed or used is also significant. The three potential limitations that exist within current environment are hardware, software, and organisation. The current computing facility is slow for symbolic processing as it was built for numerical computational only.

Another major source of problems in developing expert systems is cost. At present, a knowledge engineer extracts knowledge from human experts and laboriously builds it into the knowledge base. The effort is time-consuming, and the knowledge engineer's services are costly due to supply shortage. Most expert system prototypes would require three man- months to develop, and a usable system would take about one man-year to build. The cost of keeping the expert system up to date have to be considered also, apart from justifying whether it would be used intensively enough in practice.

In short, the best use of expert system technology at present is to enhance conventional software programs in user friendliness and in intelligent interface of databases. Expert systems are more likely to be successful if certain conditions are met such as :

a. the application area must be well bounded.

b. at least one human expert must be available to explain the knowledge for the expert system being built.

In addition, one or more of the five situations listed below must exist for an expert system to be successful :

a. shortage of specialist experts

b. need to preserve expert's knowledge

c. high cost of expert advice

d. critical requirements of expert advice

e. routine detail-dependent decision making

11.7 CONCLUSION

Expert system technology is generally acknowledged to be the rising star of artificial intelligence in the past two decades, but it is difficult to predict how expert systems will fare in the future. All technologies have a finite life span and are superseded by better innovations. Expert systems will be no exception. However, it is evident that the expert systems market is still buoyant and healthy and that the systems are making inroads in an increasing variety of areas. They are also expected to continue to develop and expand into new areas and also merge and co-exist with other software.

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CHAPTER 12

APPLICATION OF EXPERT SYSTEMS IN THE PRELIMINARY DESIGN OF OFFSHORE SUPPLY VESSELS

CHAPTER 12

APPLICATION OF EXPERT SYSTEMS IN THE PRELIMINARY DESIGN OF OFFSHORE SUPPLY VESSELS

12.0 INTRODUCTION

One of the most promising developments in the use of computers in recent years has been the work on expert systems. Its significance is that it addresses itself to providing computer systems which are able to make a 'knowledgeable' contribution to complex problems in a specific domain or field of interest such as preliminary ship design, that is, to act as an expert. In this respect, the expert system can be developed in four different modes such as :

a. the user as a client where the system acts as a consultant from whom the user wishes to get answers to problems,

b. the user as a tutor where the system accepts instructions from a domain specialist to improve or refine its knowledge,

c. the user as a pupil where the system uses its expert knowledge to instruct users in certain approaches, and

d. the user as an assistant where the system interacts with the user to encourage the user to find a solution to a problem with guidance advice and stimulation from the system.

It is the last mode which is most relevant to the ship design situation. The work described in this study is based on the contention that the approaches being taken in expert systems provide a key to realising the potential of computer-aided design. For many years, we have been building complex computer-aided design systems which contain increasing amounts of knowledge. However, that knowledge has been highly constrained to particular methods, and has been implicitly rather than explicitly available. Systems based on ideas of explicit knowledge representation and reasoning, offer the possibility of greater productivity in the contribution they make to man-machine communication.

12.1 SELECTION OF AN EXPERT SYSTEM SHELL

Instead of using one of the artificial intelligence languages such as Lisp or Prolog, and developing the whole system from basic principles through predicate logic as was done in some other marine applications [3], [8], [10] it was decided to use an expert system shell to write an extensive preliminary design program for offshore supply vessels.

Advantages of using such shells is the time saving in the development of the system, as work has already been done in the form of the user interface and inference engine does not have to be repeated, and no knowledge of artificial intelligence is required. However, in selecting the appropriate shell to be used in preliminary ship design, certain factors must be available in such a shell :

a. The ability to incorporate a knowledge representation language which allows the user to create a knowledge base using pseudo-english. The structure and syntax of the language allows non-expert programmers to construct different knowledge bases.

b. The facility to allow direct access to external analysis procedures written in procedural languages such as Fortran, Pascal, and C, together with the facility to access many applications programs.

c. The knowledge representation language is able to represent the type of heuristic knowledge associated with ship design.

d. The capability of graphical visualisation.

At present, there are numerous shell programs available in the market which are capable of working in microcomputers with prices ranging from a few hundreds to a few thousands of Pounds Sterling. In this study, an expert system shell called *Leonardo* version 4.0 is used to produce a program for the preliminary design of offshore supply vessels. *Leonardo* uses rules and an object-oriented frame system. It also contains a procedural language and includes support for Bayesian statistics, fuzzy logic, and certainty factors. It runs on *IBM XT* or *AT* compatibles with 512 K, and *MS* or *PC Dos 2.00* or above. Details on the other main features and working procedure of the Leonardo is given in Appendix C.

12.2 STRUCTURE AND CONTENT OF THE KNOWLEDGE BASE

The preliminary design knowledge base for offshore supply vessels developed for the expert system contains a considerable amount of information gathered through extensive studies on the characteristics of 20 pure supply vessels and 20 anchor handling/tug/supply vessel built since 1980. This information, or domain knowledge, is expressed in the knowledge base in terms of empiricisms, factual declarations and user-supplied design parameters. Typical examples of knowledge used in the design of offshore supply vessels are given in Fig. 12.1. The knowledge base invoked by the system comprises of a number of elements which allow the determination of the vessel's main dimension, weight groups, capacity, freeboard, initial stability, powering, propulsion characteristics, seakeeping.and manoeuvring characteristics, and economic analysis.

The main steps followed by the system during development of the design process of an offshore supply vessel proposal in shown in Fig. 12.2. The user will start the system by selecting the required type of vessel to be designed, either a pure supply vessel or an anchor handling/tug/supply vessel. On determining the type of vessel, the user will be presented with guidance on the typical functions available for each type of vessel. Having selected the type of vessel, the user will then be prompted with the requirements menu where he will define the requirement for the proposed vessel in terms of deadweight, capacity, stability, and/or speed. As for the anchor handling/tug/supply vessel, an additional requirement , that is, the bollard pull is supplied. The user may skip any design requirement which is not essential for the proposed vessel. Once the design requirement is obtained, the user will be asked for any limitation or restriction to be imposed on the main parameters of the proposed vessel. Again, the user may insert values for the length, breadth, depth and/or draught or skip all the limitations.

Once the design requirements and limitations on the main dimension are known, the program will proceed to estimate the main parameters such as length, beam, depth, draught, block coefficient and deadweight (if any of these values are not entered as input). The system will continue to evaluate the steel weight, outfit weight and the machinery weight of the vessel. The deadweight calculated in this procedure is checked with the user requirement's deadweight (if input) or the initial deadweight estimated. If the calculated deadweight is within the tolerance limit, the program will proceed to estimate the capacity of the vessel. If the calculated deadweight is not within the tolerance limit, then the process of calculating the main dimension will be repeated until the calculated deadweight is within the tolerance limit. The same procedure applies to the calculation of capacity and initial stability of the vessel.

```
/*      Rules to Obtain Main Dimensions of Vessel

        if input_data is known
        and main_dimension is obtained
        then dimension_of_vessel is available

/*      Rules to Generate Hullform

        if dimension_of_vessel is available
        and hull_form is generated
        then vessel_shape is obtained


/*      Rules to Calculate Propeller Characteristics

        if vessel_effective_power is obtained
        and type_of_vessel is pure_supply
        and rpm_of_engine > 0.0
        then use screen7;
        blade_number is known

        if blade_number is known
        then run propeller_characteristics (length, beam, depth, draught, ehp,
                block_coefficient, speed, displacement, dia_propeller,
                pitch, bhp);
        propeller_characteristics is obtainable


/*      Rules to Calculate Shipbuilding Costs

        if ask_cost is done
        and cost_estimation is yes
        and wage_rate > 0.0
        and material_cost > 0.0
        and type_of_vessel is pure_supply
        then run building_costs ( steelweight, outfitweight, machineryweight,
                length, beam, depth, block_coefficient, material_costs,
                wage_rate, material_cost, shipbuilding_costs);
        building_costs is known
```

Fig. 12.1 Examples of the Rules used in the Preliminary Design of Offshore Supply Vessels

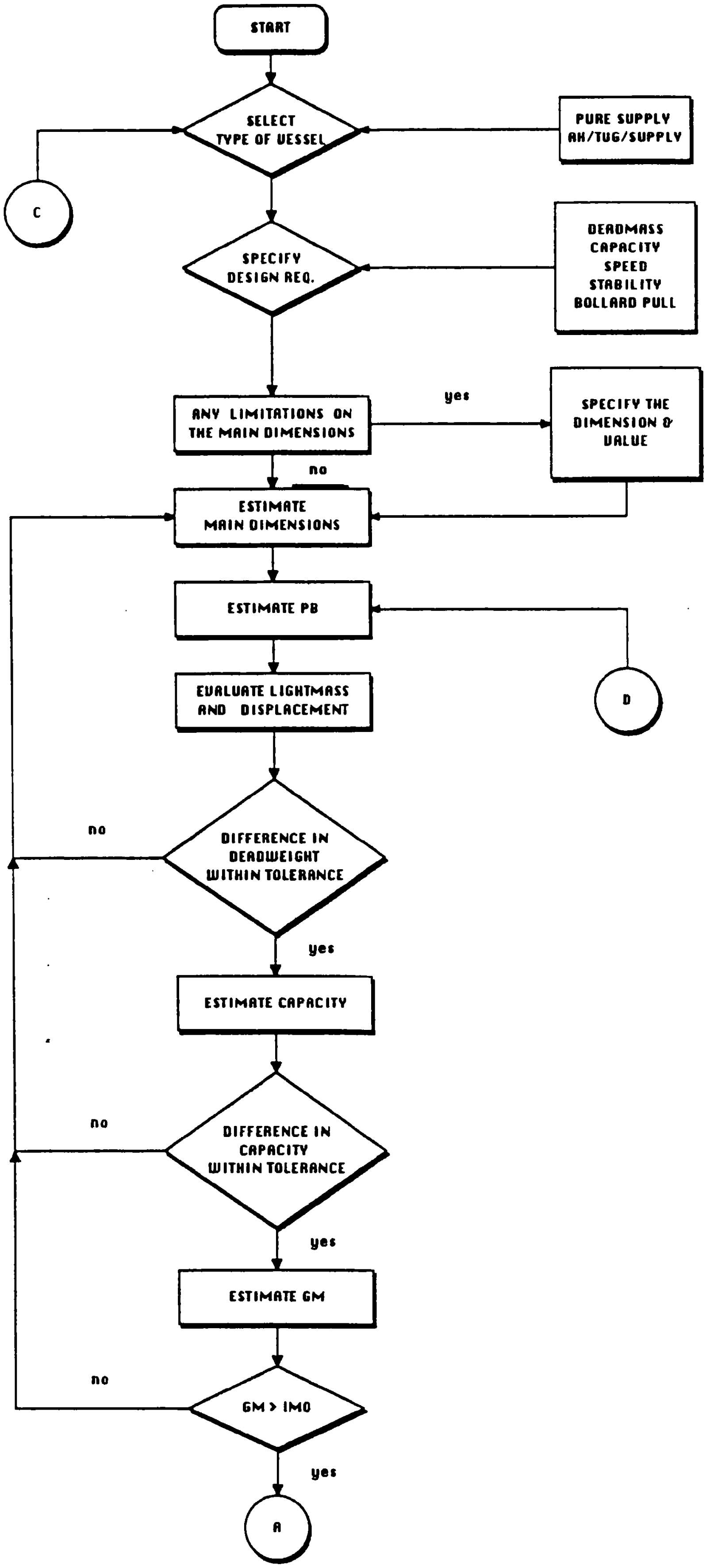

Fig. 12.2 Computer Algorithm Flowchart

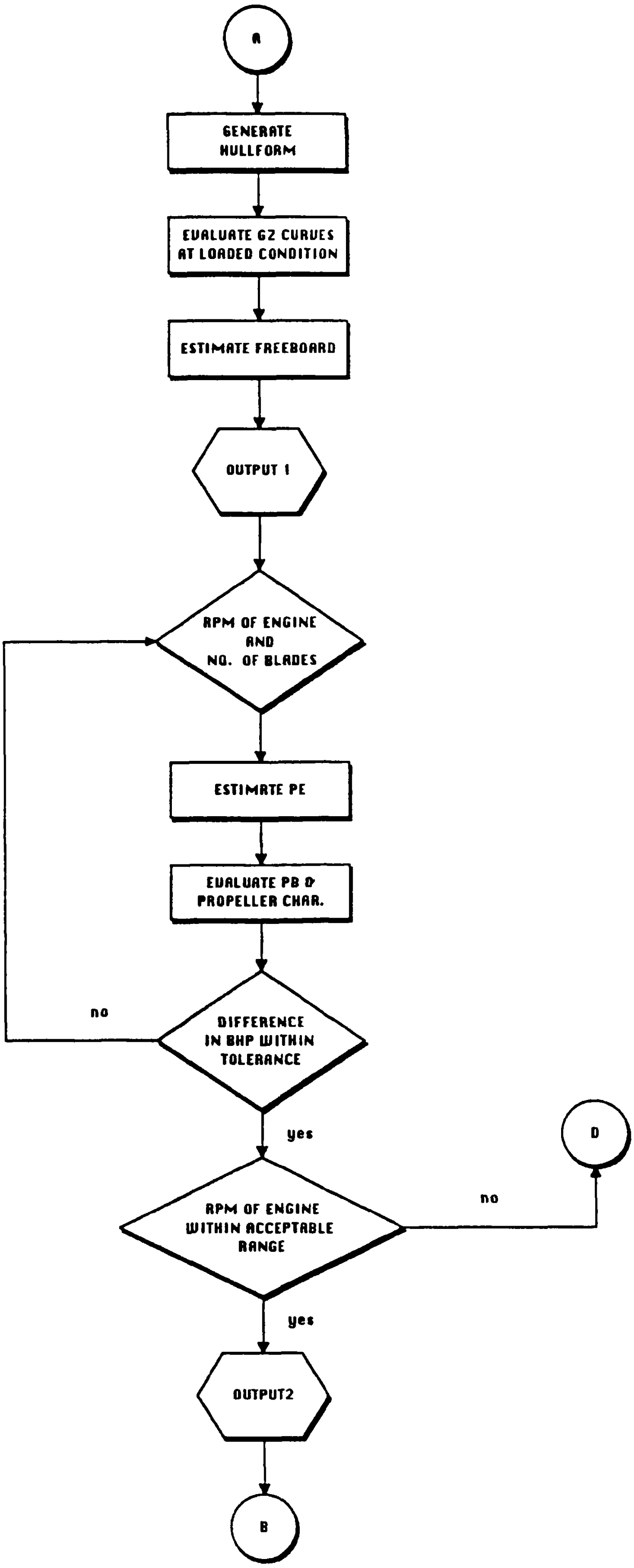

Fig. 12.2 Computer Algorithm Flowchart (continue)

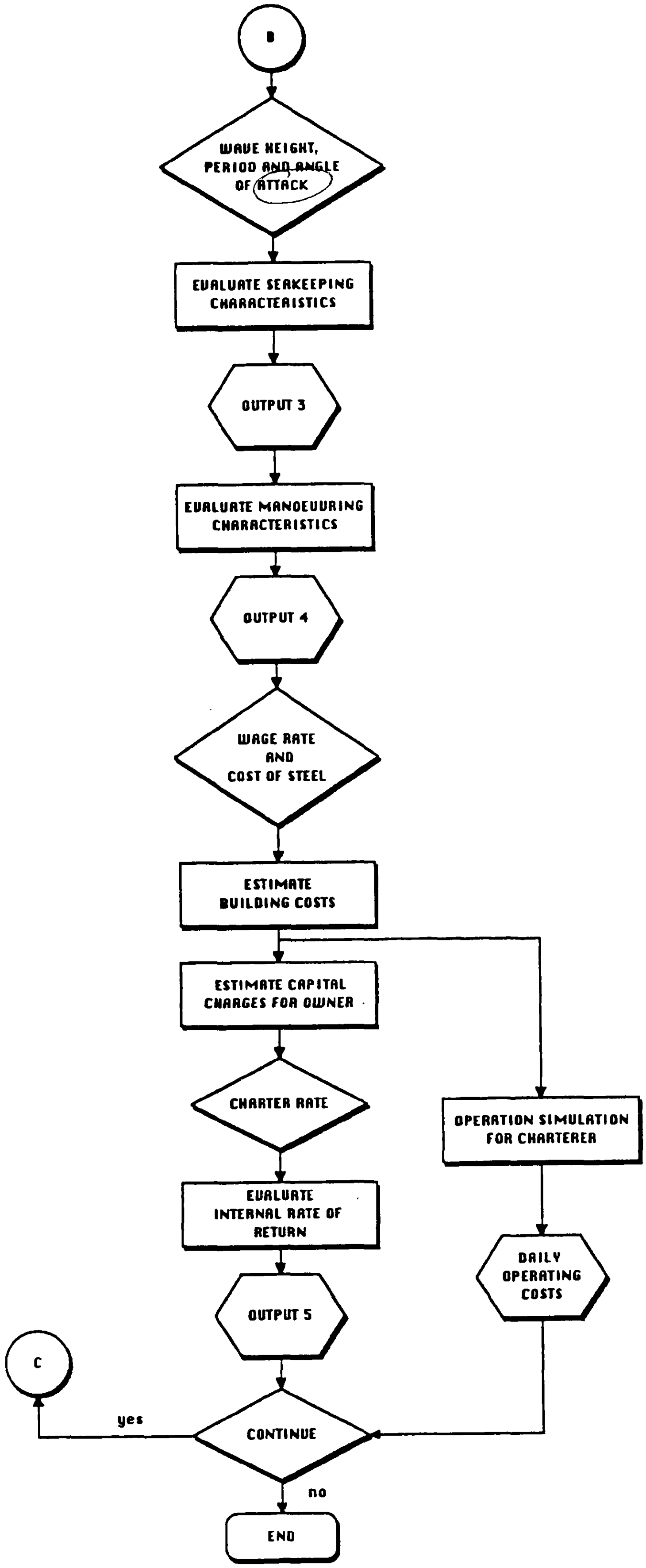

Fig. 12.2 Computer Algorithm Flowchart (continue)

After evaluating the above parameters, the system will proceed to generate the hull form of the vessel. The hull form is developed from an initial sketch of the vessel profile combined with four sectional curves. The curves are generated by a mixture of several curve fitting methods such as B-spline, parabolic blending, cubic spline and tangential arc. Full details of the development of the hull form is given in Appendix A.

Once the hull form is generated and the offset data are known, the system will calculate the effective power of the vessel. For both the pure supply vessel and anchor handling/tug/supply vessel, the design speed will be used to estimate the power. The total brake power of the anchor handling/tug/ supply vessel will be estimated based on the assumption that the vessel's towing speed is 0.6 of the free running design speed together with the required bollard pull. Before the system proceeds with the evaluation of the propeller characteristics, the user will be asked for the rpm of engine and the number of blades for the propeller. The user will be guided in selecting the rpm of engine and the number of blades suitable for offshore supply vessel design. In determining the propeller characteristics for the pure supply vessel, the optimum efficiency method will be used and checked with a cavitation criteria. The anchor handling/tug/supply vessel propeller characteristics will be determined by the design for the bollard pull requirement.

The system will then proceed to evaluate the minimum freeboard required by the regulations. Before proceeding with the seakeeping analysis, the user will be asked to input the wave height, wave period and the angle of attack of the waves. The output of the seakeeping analysis will include the natural heave, pitch and roll period as well as the response to irregular waves. The system will then evaluate the manoeuvring characteristics of the vessel which will include the minimum area for the rudders.

The user will then be asked whether to proceed with the economic analysis or not. If the user chooses not to proceed with such analysis, the system will asked whether, he may wish to run the program again. If the user chooses to proceed with the economic analysis, he will be asked to input the average wage rate and the cost of steel per ton before the evaluation of the shipbuilding cost is done. Again, the user is guided with the updated values of the average wage rate and steel cost in the United Kingdom. Once the shipbuilding cost is evaluated, the user will be asked whether the vessel is to be chartered or the owner will be operating the vessel. If the vessel will be chartered, the user acting as the charterer may run the operating simulation program to estimate the minimum operating costs described in detail in Chapter 9. If the vessel is to be operated by the owner, the user acting as the owner will be prompted for the charter rate expected and the discount rate as a in percentage. The system will then evaluate the capital charges and the internal rate of return based on the assumptions given in Chapter 8.

For any user who is familiar with the system, facilities are available where he may insert all the input data at the beginning of the program so that the program will evaluate all the output without any disruption. As for user who wishes to know how each value of output is obtained, he may ask the system how the value is calculated. Access to any evaluations can be given by referring to the necessary frame.

12.3 EXAMPLE OF EXECUTION

The example given in this study concerns the development of a pure supply vessel design proposal with the owner's requirement of a deadweight of 1200 tonnes and speed of 13.5 knot. No restriction on the main dimensions are given. The stability and minimal freeboard of the vessel must conform with the IMO regulations.

Figures 12.3 and 12.4 shows the ship profile and part of the body plan developed from the initial sketch technique. Figure 12.5 shows the main parameters of the vessel while Fig. 12.6 gives the stability condition of the vessel when fully loaded. The powering and propulsion results are shown in Fig. 12.7 and are followed by Fig. 12.8 and Fig. 12.9 which give the seakeeping and manoeuvring characteristics respectively of the vessel to be designed. Finally, the shipbuilding costs of the vessel are given in Fig. 12.10 which reflect the building cost if the vessel is to be built in United Kingdom.

12.4 CONCLUSION

This study has been concerned with presenting an overall knowledge-based approach to handling numerical relationships in the preliminary design of offshore supply vessels. Many details of the system have not been discussed as the aim was to convey the salient features of the system and to illustrate the overall concept involved. However, it is worth emphasising a number of points with respect to the usage of an expert system shell in preliminary ship design :

a. the user of the system has a large degree of control over the process of the design especially in terms of the rate of progress,

b. the more the user is involved in the design process, the more he understands the design methodology,

c. the system uses built-in expertise to look for suitable relationships, thus only a part of the total model definition is active at one time.

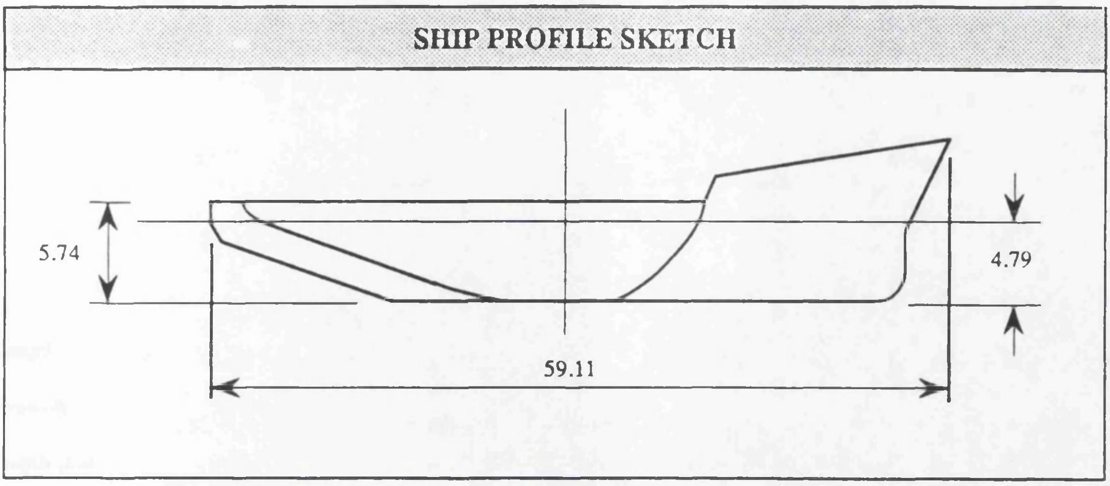

Fig. 12.3 Profile of Vessel

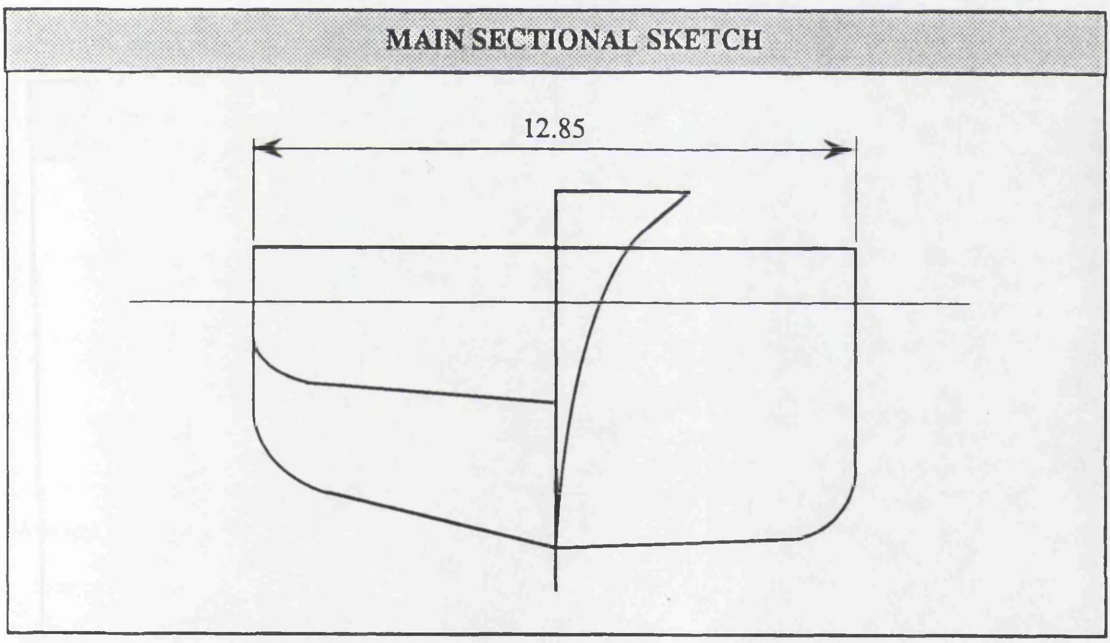

Fig. 12.4 Main Sections of Vessel

MAIN PARAMETERS OF VESSEL

Type of Vessel : Offshore Supply Vessel

Deadweight : 1200 tonnes

Speed : 13.5 knots

Length Bet. Per. (m)	:	52.58	Displacement (t)	:	2322.00	Underdeck Capacity (m^3)	:	2807.00
Breadth (m)	:	12.85	Steel Mass (t)	:	688.00	Block Coefficient	:	0.71
Depth (m)	:	5.74	Outfit Mass (t)	:	174.70	Prismatic Coefficient	:	0.76
Draught (m)	:	4.79	Machinery Mass (t)	:	249.00	Midship Coefficient	:	0.94
Min. Freeboard (m)	:	0.90	Margin Mass (t)	:	10.30	Waterplane Area Coeff.	:	0.78

Fig. 12.5 Main Parameters of Vessel

STABILITY CONDITION AT FULL LOAD

Angle of Heel	:	0	10	20	30	40	50	60
GZ (m)	:	0	0.16	0.28	0.52	0.62	0.59	0.45

GM at loaded condition (m) = 2.470

Area under curve up to 40^{o} (m/rad) = 0.226

Area under curve up to 30^{o} (m/rad) = 0.120

Area between 40^{o} and 30^{o} (m/rad) = 0.106

Downflooding Angle = 40^{o}

Fig. 12.6 Stability at Full Load Condition

POWERING AND PROPULSION

Design Speed of Vessel	:	13.5 knots
Displacement of Vessel	:	2322 tonnes
Number of Screws	:	2

Effective Power (kW)	:	1310.000	Number of Propeller Blades	:	4
Brake Power (kW)	:	2442.000	Diameter of Propeller (m)	:	1.803
RPM of Engine (rev/min)	:	1200.000	Blade Area Ratio (BAR)	:	0.400

Fig. 12.7 Power and Propulsion Estimation

SEAKEEPING CHARACTERISTICS

Natural Heave Period	:	5.19 sec.
Natural Pitch Period	:	4.52 sec.
Natural Roll Period	:	6.51 sec.

Results for Seakeeping Characteristics in Irregular Sea Conditions

Wave Height	:	5.0 m
Wave Period	:	10.0 sec.
Angle of Attack	:	180^{o}

		Wave		Heave		Pitch		Roll	
Average Amplitude	:	1.16	m	2.60	m	2.31	deg.	0.00	deg.
Significant Amplitude	:	1.85	m	4.16	m	3.69	deg.	0.00	deg.
Significant Velocity	:	1.17	m/s	3.21	m/s	2.95	deg/s	0.00	deg/s
Significant Acceleration	:	1.00	m/s^2	2.63	m/s^2	2.70	deg/s^2	0.00	deg/s^2

Fig. 12.8 Seakeeping Characteristics of Vessel

MANOEUVRING ANALYSIS RESULTS

INPUT VERIFICATION :

LENGTH (m)	=	59.11
BEAM (m)	=	12.85
MEAN DRAFT (m)	=	4.79
BLOCK COEFFICIENT	=	0.71
CENTRE OF GRAVITY (m from midship)	=	0.037
INITIAL VESSEL SPEED (knot)	=	13.50
RADIUS OF GYRATION (m)	=	0.25 x L
WATER DEPTH TO VESSEL DRAUGHT RATIO (m)	=	1000.0
NUMBER OF PROPELLERS	=	2

LINEAR MANOEUVRING DERIVATIVES

NONDIMENSIONAL MASS	M PRIME	=	0.02140
NONDIMENSIONAL MASS MOMENT	I SUB ZZ	=	0.00134
SWAY VELOCITY DERIVATIVE	Y SUB V	=	-0.03273
SWAY ACCELERATION DERIVATIVE	Y SUB V DOT	=	-0.01989
YAW VELOCITY DERIVATIVE	N SUB V	=	-0.01300
YAW ACCELERATION DERIVATIVE	N SUB V DOT	=	-0.00235
SWAY VELOCITY DERIVATIVE	Y SUB R	=	0.00465
SWAY ACCELERATION DERIVATIVE	Y SUB R DOT	=	-0.00227
YAW VELOCITY DERIVATIVE	N SUB R	=	-0.00450
YAW ACCELERATION DERIVATIVE	N SUB R DOT	=	-0.00081
SWAY RUDDER DERIVATIVE	Y SUB DELTA	=	0.00513
YAW RUDDER DERIVATIVE	N SUB DELTA	=	-0.00256

TIME CONSTANTS AND GAINS FOR NOMOTO'S EQUATION

DOMINANT SHIP TIME CONSTANT	T1 PRIME	=	4.54117
SHIP TIME CONSTANT	T2 PRIME	=	0.37270
NUMERATOR TIME CONSTANT	T3 PRIME	=	0.80804
NUMERATOR TIME CONSTANT	T4 PRIME	=	0.27241
1ST ORDER EQN. TIME CONSTANT	T PRIME	=	4.10583
RUDDER GAIN FACTOR	K PRIME	=	3.21215
RUDDER GAIN FACTOR	K SUB V PRIME	=	1.48745
RUDDER AREA (m^2)	ARUD	=	5.969

EVALUATION OF TURNING ABILITY AND STABILITY

CLARKE'S TURNING INDEX	P	=	0.39117
LINEAR DYN. STAB. CRITERION	C	=	-0.08546

COMMENTARY : *VESSEL IS NOT COURSE STABLE*

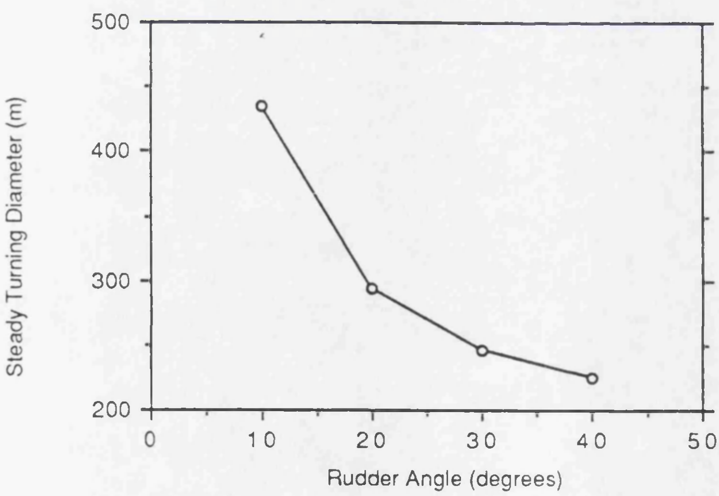

Fig. 12.9a Effects of Rudder Deflection on Steady Turning Diameter

Fig. 12.9 Manoeuvring Characteristics of Vessel

SHIPBUILDING COSTS

Average Wage Rate	:	£6.05 per hour
Cost of Steel	:	£300 per tonne

Steel Material Costs (£)	:	249808.00	Steel Labour Costs (£)	:	1442229.00
Outfit Material Costs (£)	:	607275.00	Outfit Labour Costs (£)	:	1143657.00
Mach. Material Costs (£)	:	1936165.00	Mach. Labour Costs (£)	:	1224079.00
Miscellaneous Costs (£)	:	336801.00			

Total Shipbuilding Costs (£)	:	6940014.00

Fig. 12.10 Shipbuilding Costs of Vessel

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CHAPTER 13

AN INTERACTIVE OPTIMISATION EXPERT SYSTEM FOR THE PRELIMINARY DESIGN OF OFFSHORE SUPPLY VESSELS

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AN INTERACTIVE OPTIMISATION EXPERT SYSTEM FOR THE PRELIMINARY DESIGN OF OFFSHORE SUPPLY VESSELS

13.0 INTRODUCTION

It has always been a challenge for designers to produce efficient and cost-effective systems. The conventional design process depends on the designer's intuition, experience and skill. Figure 13.1 shows the self-explanatory flow chart for a conventional design process that involves the use of information gathered from one or more trial designs together with the designer's experience and intuition.

Scarcity and need for efficiency in today's competitive world has forced designers to evince greater interest in economical and better designs. With recent advances in computer technology affecting various disciplines of engineering, the design process can hardly remained untouched. Design is not only regarded as the more or less intuitively guided creation of new information but is comprised of analysis, presentation of results, simulation and optimisation. These are essential constituents of an iterative process leading to a feasible and finally optimum design. Figure 13.2 shows the optimum design process.

The optimum design process forces the designer to identify explicitly a set of design variables, a cost function to be minimised, and the constraint functions for the system. This rigorous formulation of the design problem helps the designer to gain a better understanding of the problem. However, the optimisation process can benefit substantially from the designer's experience and intuition. Thus, the best approach would be to have an optimum design process that is aided by interaction with the designer.

Several methods for optimum design of systems have been developed over the past two decades, and preliminary ship design is no exemption. They harness a computer's speed with computational algorithms to methodically generate efficient designs which are needed in today's competitive world. Nevertheless, most of the methods work well only when used by optimisation experts. Designers who are not optimisation experts have difficulties in making the algorithms and programs work for

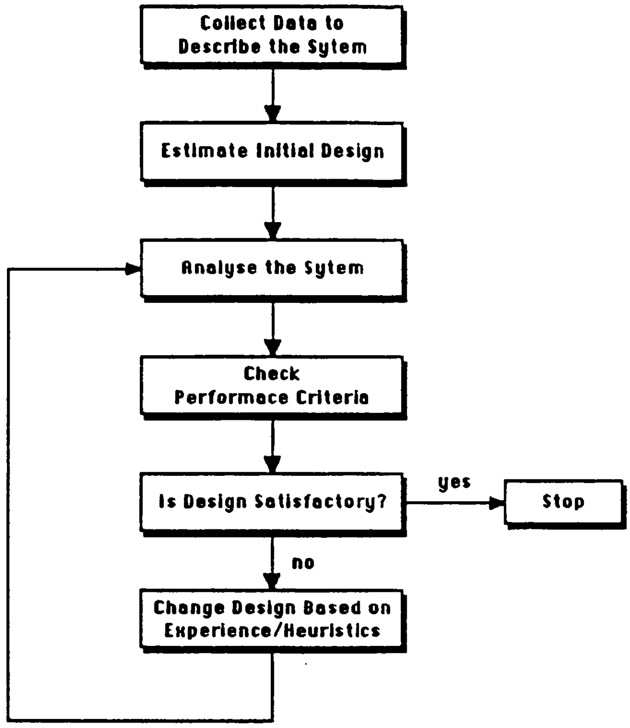


Fig. 13.1 Conventional Design Process

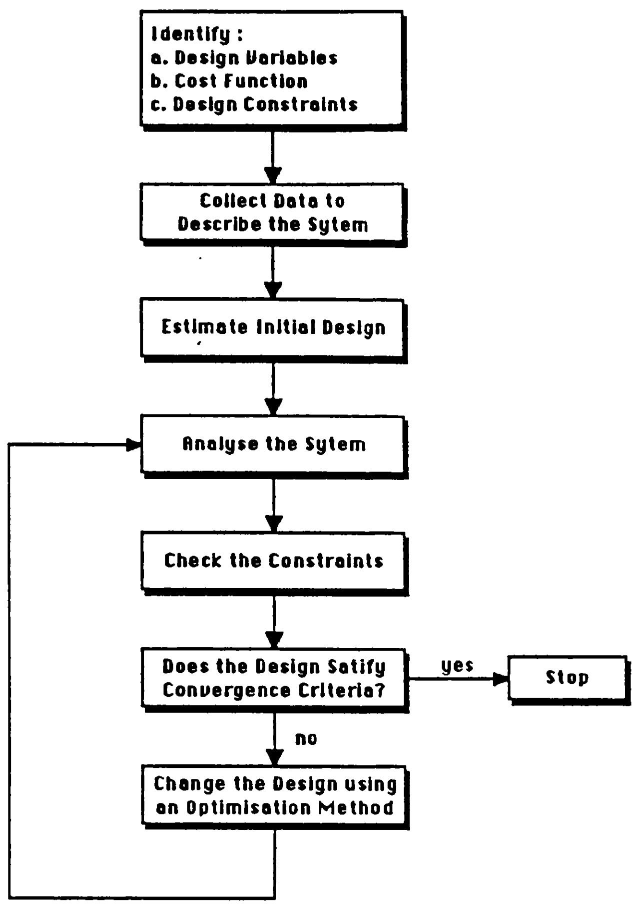


Fig. 13.2 Optimum Design Process

their application. This indicates that the rules used by the expert in making the program work should be captured and put in the knowledge base to be consulted the designers. Such a system should be well designed for knowledge acquisition and utilisation.

This section describes attributes of an expert system for design optimisation for the preliminary design of offshore supply vessels. This study will be based on non-linear constrained optimisation concept developed by *Hooke* and *Jeeves* [7] and *Nelder* and *Mead* [5].

13.1 FUNDAMENTALS OF OPTIMISATION CONCEPT

This section will briefly discuss some of the fundamental ideas and methods of mathematical programming. The discussion will focus on the basic ideas of how and why these procedures work; mathematical detail is intentionally avoided as much as possible. Full detail on the optimisation methods together with their mathematical formulation are given in numerous texts such as [6], [10] and [11].

13.1.1 Problem Formulation

Formulation of an optimum design problem involves transcribing a verbal description of the problem into a well-defined mathematical statement. The formulation process begins by identifying a set of variables to describe the system, called design variables. Once the variables are given numerical values, a design system is produced.

All systems are designed to perform within a given set of constraints which include limitation on resources, material failure, response of system and member size. The constraints must be influenced by the design variables of the system, because only then can they be imposed. If a design satisfies all the constraints, a feasible (workable) system is obtained.

A criterion is need to judge whether or not one design is better than another. This criterion is called the objective function or cost function. A valid objective function must be influenced by the variables of the design problem, that is it must be a function of the design variables.

The importance of proper formulation of a design optimisation problem must be clearly understood since the optimum solution will only be as good as the formulation.

For example, if a critical constraint is forgotten in the formulation, the optimum solution will most likely violate it because optimisation methods tend to exploit errors or uncertainties in the design models. If constraints are not properly formulated, the optimisation techniques will take designs into portions of the design space where either the design is absurd or dangerous. However, if there are too many constraints on the system or if they are inconsistent, there may not be any solution to the design problem. Therefore, a careful formulation of the design problem is of paramount importance and proper care should always be exercised in defining and developing expressions for the constraints.

13.1.1.1 Design Variables

Parameters chosen to describe the design of a system are called the design variables. These variables are regarded as free because the designer can assign any value to them. In preliminary ship design, they might include length, beam, breadth, speed, and block coefficient.

An important first step in the proper formulation of the problem is to identify design variables for the system. If proper variables are not selected, the formulation will be either incorrect, or not possible at all. At the initial stage of the problem formulation, all options of identifying design variables should be investigated. Sometimes it is desirable to designate more design variables than may be apparent from the statement of the problem. This gives an added realism in the problem formulation. Later, it is possible to assign fixed numerical values to any variable and thus eliminate it from the problem formulation. Another important factor is that all design variables should be independent of each other as far as possible. One should be able to assign numerical values to any variable independent of any other variable.

13.1.1.2 Design Constraints

All restrictions placed on a design are collectively called constraints. Each constraints must be influenced by one or more design variables. Only then is it meaningful and does it have influence on optimum design. Some constraints are quite simple, such as the minimum and maximum value of the design variables, while more complex ones may be indirectly influenced by the design variables. Many constraint functions have only first-order terms in the design variables which are called linear constraints, whereas more general problems have nonlinear constraint functions as well. Thus, methods to treat both linear and nonlinear constraints must be developed.

In practice, design problems may have equality as well as inequality constraints. A typical example of equality constraint in preliminary ship design is that a ship might be required to have a specified deadmass. A feasible design must satisfy precisely such equality constraint. Examples of inequality constraints are that calculated stresses must not exceed allowable stress of the material, deflection must not exceed specified limits, fundamental vibration frequency must be higher than the operating frequency. Note that there are many feasible designs with respect to an inequality constraint. For example, any design having calculated stress less than or equal to the allowable stress is feasible with respect to that constraint. A large number of designs satisfy this constraint. A feasible design with respect to an equality constraint, however, must lie on its surface. Thus, the feasible region for the inequality constraints is much larger than the one for the same constraint expressed as an equality. It is easier to find feasible designs for a system having only inequality constraints. Figure 13.3 illustrate the difference between equality and inequality constraints.

13.1.2 Standard Design Optimisation Model

The standard design optimisation model is defined as follows : Find an n-vector $x = (x_1, x_2, \ldots\ldots, x_n)$ of the design variables to minimise an objective function

$$f(x) = f(x_1, x_2, \ldots\ldots, x_n) \qquad \text{Eqn. 13.1}$$

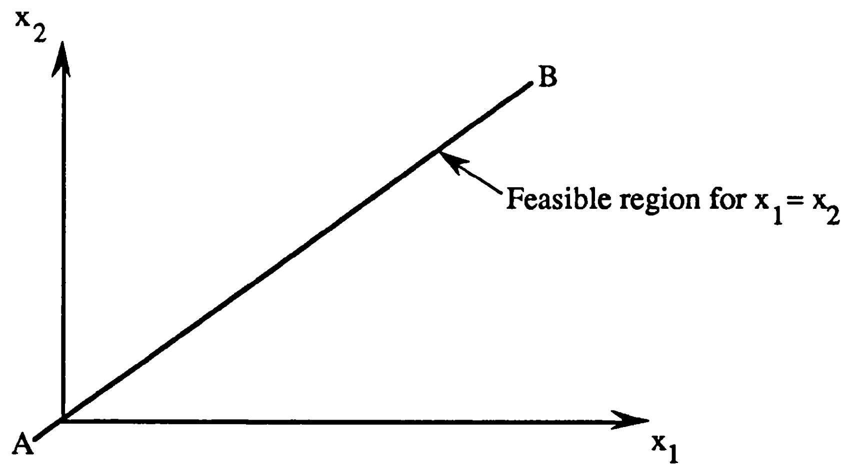
subject to the p equality constraints

$$h_j(x) \equiv h_j(x_1, x_2, \ldots\ldots, x_n) = 0; \qquad j = 1 \text{ to } p \qquad \text{Eqn. 13.2}$$

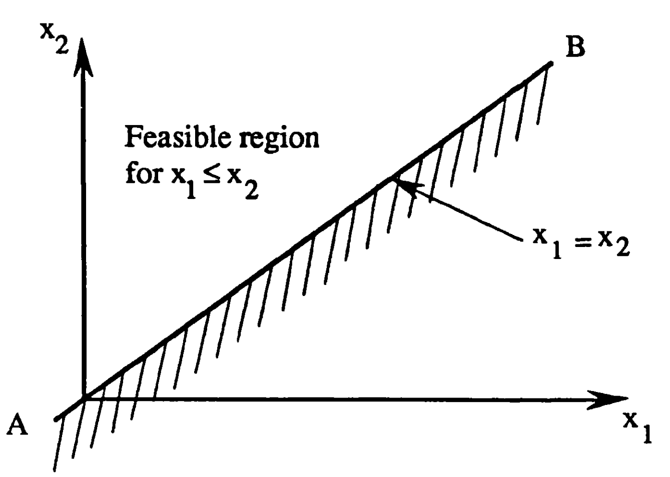
and the m inequality constraints

$$g_i(x) \equiv g_i(x_1, x_2, \ldots\ldots, x_n) \geq 0; \qquad i = 1 \text{ to } m \qquad \text{Eqn. 13.3}$$

where p is the total number of equality constraints and m is the total number of inequality constraints. Note that the simple bounds on the design variables such as $x_i \geq 0$, $i = 1$ to n, or $x_{il} \leq x_i \leq x_{iu}$, $i = 1$ to n where x_{il} and x_{iu} are the smallest and



(a) Feasible Region for Constant $x_1 = x_2$ (line A - B)



(b) Feasible region for constant $x_1 \leq x_2$ (line A - B and region above it)

Fig. 13.3 Distinction Between Equality and Inequality Constraints the largest allowed value for x_i, are included in the equalities of Eqn. 13.3. In numerical methods, these constraints can be treated more efficiently in the original form without converting them to the form of Eqn. 13.3.

Design optimisation problems from different fields of engineering can be transcribed into the standard model. Thus, the standard model is quite general. It is important to note that once design problems from different fields are transcribed into the standard model, they all look alike.

13.2 SELECTION OF OPTIMISATION ALGORITHM

Search methods for use on multivariable unconstrained problems have rapidly increased in number and sophistication in recent years. While all realistic problems are constrained, an unconstrained building block is often required. The unconstrained methods are normally divided into two categories, derivative free methods and gradient methods.

The gradient methods require function and derivative evaluations while the derivative free methods require function evaluations only. In general, one would expect the gradient methods to be more effective, due to the added information provided. However, if analytical derivatives are available, the question of whether a search technique should be used at all is presented. If numerical derivative approximations are utilised, the efficiency of the gradient methods should be approximately the same as that of the derivative free methods. Gradient methods incorporating numerical derivatives would be expected to present some numerical problems in the vicinity of the optimum, that is, the approximations would become very small.

In this studies, two well known methods will be utilised; the *Nelder* and *Mead* algorithm and the *Hooke* and *Jeeves* algorithm.

13.2.1 Nelder and Mead Algorithm

This algorithm is an extension of the simplex method by *Spendley*, *Hext* and *Himsworth* [18]. Both methods utilise a regular geometric figure (called a simplex) consisting (N + 1) vertices. This method accelerates the simplex method and makes it more general. It adapts itself to the local landscape, using reflected, expanded, and contracted points to locate the minimum. Unimodality is assumed and thus several sets of starting points should be considered. Derivatives are not required. The algorithm proceeds as follows :

a. A starting point, X_1, is selected.

b. A starting simplex is constructed consisting of the starting point and the following additional points:

$$X_j = X_1 + \xi_j \qquad j = 2, 3, \ldots, N+1 \qquad \text{Eqn. 13.4}$$

where ξ_j is determined from the following table,

j	$\xi_{1,j}$	$\xi_{2,j}$	⇒	$\xi_{N-1,j}$	$\xi_{N,j}$
2	p	q	⇒	q	q
3	q	p	⇒	q	q
⇓	⇓	⇓	⇒	⇓	⇓
⇓	⇓	⇓	⇒	⇓	⇓
N	q	q	⇒	p	q
N + 1	q	q	⇒	q	p

N = total number of variables

a = side length of simplex

$$p = \frac{a}{N\sqrt{2}}\left(\sqrt{N+1} + N - 1\right)$$

$$q = \frac{a}{N\sqrt{2}}\left(\sqrt{N+1} - 1\right)$$

c. Once the simplex is formed, the objective function is evaluated at each point. The worst point (highest value of the objective function) is replaced by a new point. Three operations are used: reflection, contraction and expansion. A reflected point is located first as follows:

$$X_{i,j}\ (\text{reflected}) = X_{i,c} + \alpha(X_{i,c} - X_{i,j}\ (\text{worst})) \qquad \text{Eqn. 13.5}$$

where α is a positive constant.

$X_{i,c}$ are the centroid coordinates of all points excluding the worst point and are calculated from the following:

$$X_{i,c} = \frac{1}{K-1}\left[\sum_{j=1}^{K} X_{i,j} - X_{i,j}(\text{worst})\right] \qquad i = 1, 2, \ldots, N$$

Eqn. 13.6

where K = N + 1

d. If the reflected point has the worst objective function value of the current points, a contracted point is located as follows:

$$X_{i,j}\ (\text{contracted}) = X_{i,c} - \beta(X_{i,c} - X_{i,j}(\text{worst})) \qquad i = 1, 2, \ldots, N$$

Eqn. 13.7

where β lies between 0 and 1.

If the reflected point is better than the worst point but is not the best point, a contracted point is calculated from the reflected point as follows:

$$X_{i,j}\ (\text{contracted}) = X_{i,c} - \beta(X_{i,c} - X_{i,j}(\text{reflected})) \qquad i = 1, 2, \ldots, N$$

Eqn. 13.8

The objective function is now evaluated at the contracted point. If an improvement over the current points is achieved, the process is restarted. If an improvement is not achieved, the points are moved one half the distance toward the best point:

$$X_{i,j}\ (\text{new}) = (X_{i,j}(\text{best}) + X_{i,j}(\text{old}))/2 \qquad i = 1, 2, \ldots, N \qquad \text{Eqn. 13.9}$$

The process is then restarted.

e. If the reflected point calculated in step (c) is the best point, an expansion point is calculated as follows:

$$X_{i,j}\ (\text{expansion}) = X_{i,c} - \gamma(X_{i,j}(\text{reflected}) - X_{i,c}) \qquad i = 1, 2, \ldots, N$$

Eqn. 13.10

where γ is a positive constant. If the expansion point is an improvement over the reflected point, the reflected point is replaced by the expansion point and the process restarted. If the expansion point is not an improvement over the reflected point, the reflected point is retained and the process is restarted.

f. The procedure is terminated when the convergence criterion is satisfied or a specified number of iterations has been exceeded.

A flow chart illustrating the procedure is given in Fig. 13.4.

13.2.2 Hooke and Jeeves Algorithm

This procedure is based on the direct search method proposed by *Hooke* and *Jeeves* [7]. No derivatives are required. The procedure assumes a unimodal function; therefore, if more than one minimum exists or the shape of the surface is unknown, several sets of starting values are recommended. The algorithm proceeds as follows:

a. A base point is picked and the objective function is evaluated.

b. Local searches are made in each direction by stepping X_i a distance S_i to each side and evaluating the objective function to see if a lower function value is obtained.

c. If there is no function decrease, the step size is reduced and the searches are made from the previous best point.

d. If the value of the objective function has decreased, a 'temporary head', $X_{i,o}{}^{(k+1)}$, is located using the two previous base points $X_i{}^{(k+1)}$ and $X_i{}^{(k)}$:

$$X_{i,o}^{(k+1)} = X_i^{(k+1)} + \alpha(X_i^{(k+1)} - X_i^{(k)}) \qquad \text{Eqn. 13.11}$$

where i is the variable index = 1, 2, . . . , N
o denotes the temporary head
k is stage index (a stage is the end of N searches)
α is an acceleration factor $\alpha \geq 1.0$

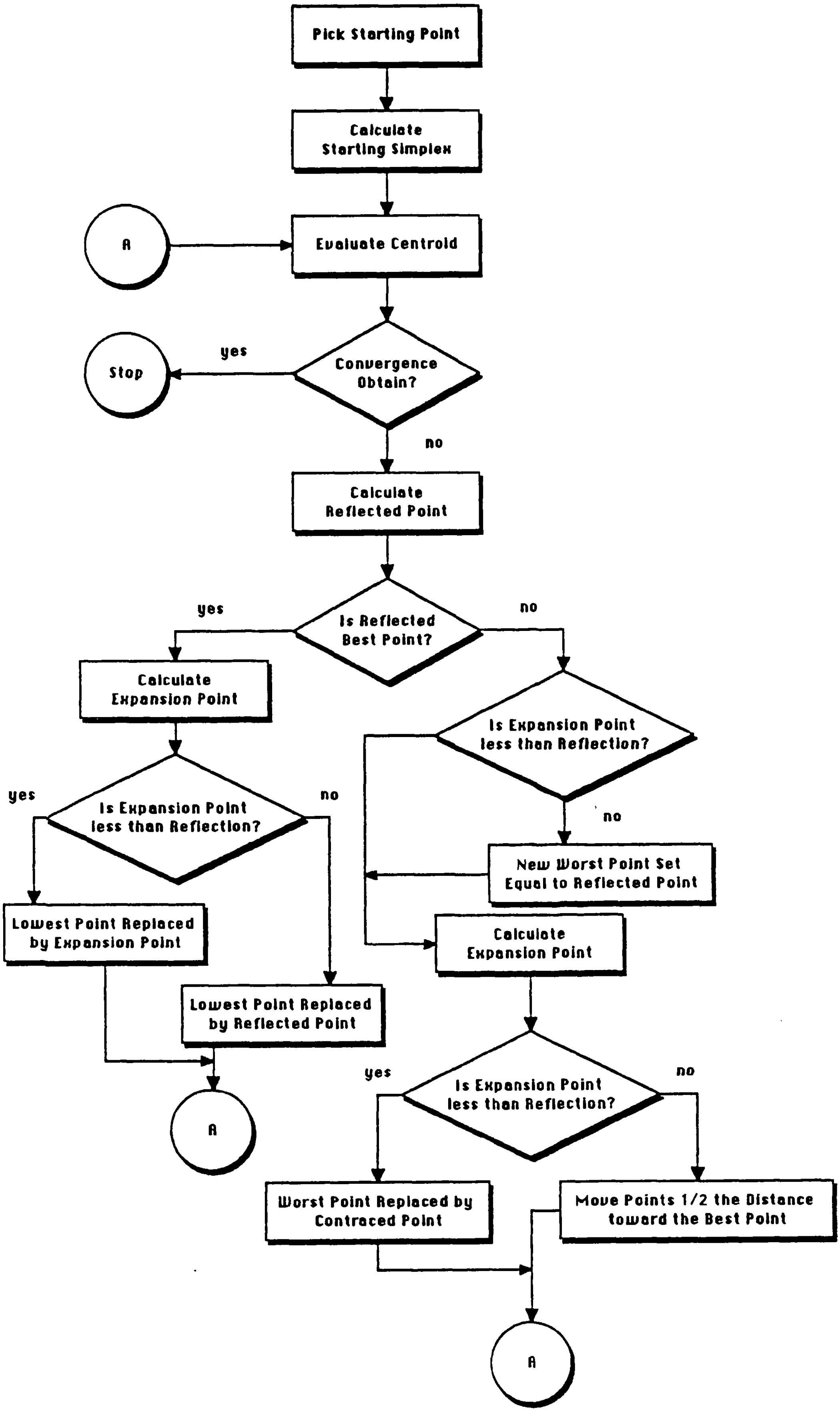


Fig. 13.4 Flow Chart for Nelder and Mead Algorithm

e. If the temporary head results in a lower function value, a new local search is performed about the temporary head, a new head is located and the value of objective is checked. This expansion continues as long as the objective function decreases.

f. If the temporary head does not result in a lower function value, a search is made from the previous best point.

g. The procedure terminates when the convergence criterion is satisfied.

A flow chart illustrating the above procedure is given in Fig. 13.5.

13.2.3 Transformation Into Constrained Optimisation Problem

Unconstrained optimisation methods can be used to solve constrained problems. The basic idea is to construct a composite function using the objective and constraint functions. It also contains certain parameters, called the penalty parameters, that penalise the composite function for violation of the constraints. The larger the violation, the larger is the penalty. Once the composite function is defined for a set of penalty parameters, it is minimised using any of the unconstrained optimisation techniques. There are several varieties of penalty function methods, however in this study, it will be restricted to the external penalty function method.

Two versions of the external penalty technique as presented by Zangwill [15], [16] use the penalty functions

$$P(\overline{x}, r_k) = F(\overline{x}) - r_k \sum_{j=1}^{p} \min(g_j(\overline{x}), 0) \qquad \text{Eqn. 13.12}$$

and

$$P(\overline{x}, r_k) = F(\overline{x}) + r_k \sum_{j=1}^{p} [\min(g_j(\overline{x}), 0)]^2 \qquad \text{Eqn. 13.13}$$

which are illustrated in Fig. 13.6. These methods permit infeasible initial and intermediate points during the solution process. If the value of r_k is sufficiently large, only a single unconstrained solution for the minimum of $P(\overline{x}, r_k)$ is required. This can be a significant advantage over Sequential Unconstrained Minimisation Techniques (SUMT) where at least three values of r_k are needed. These methods, especially Eqn.

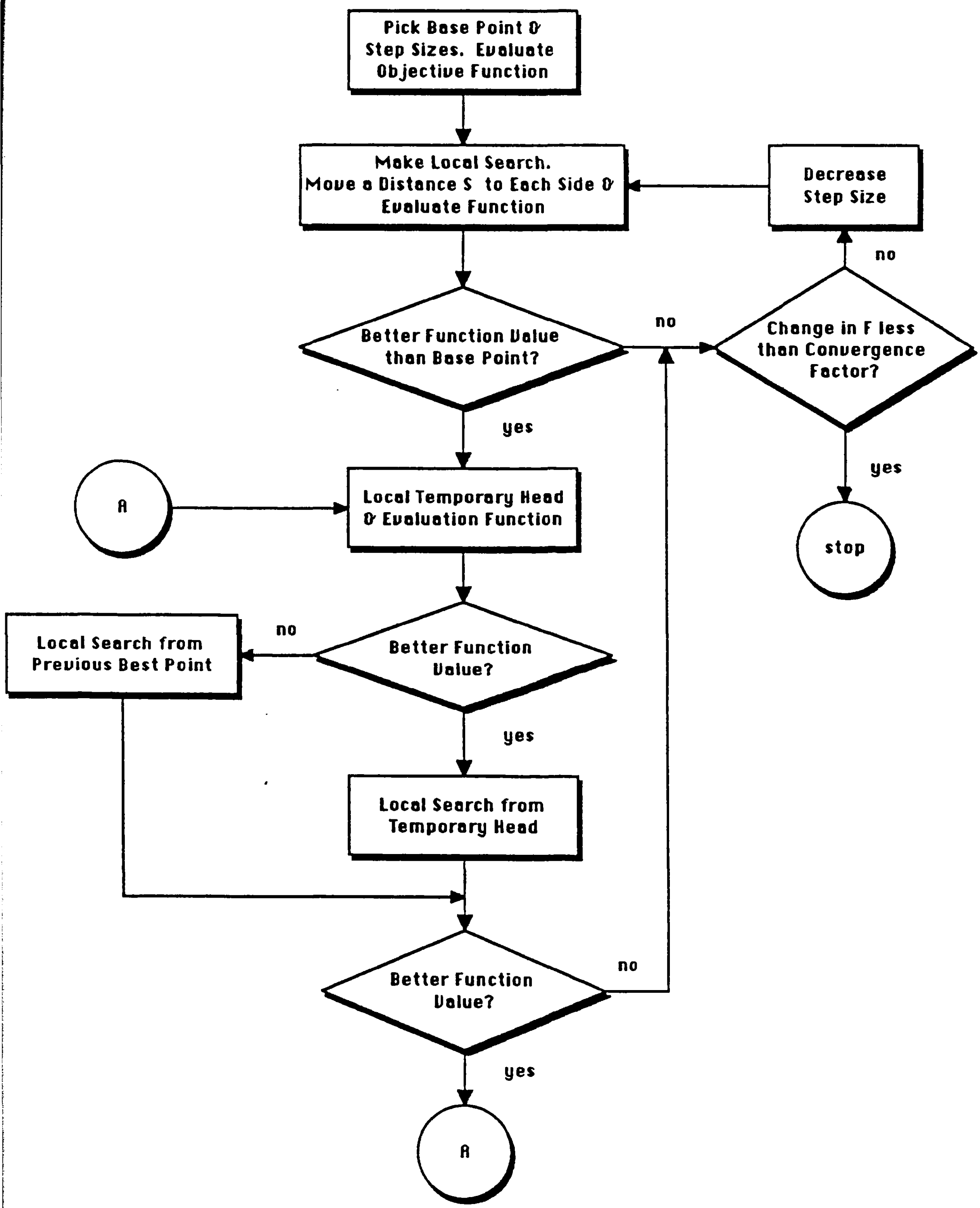


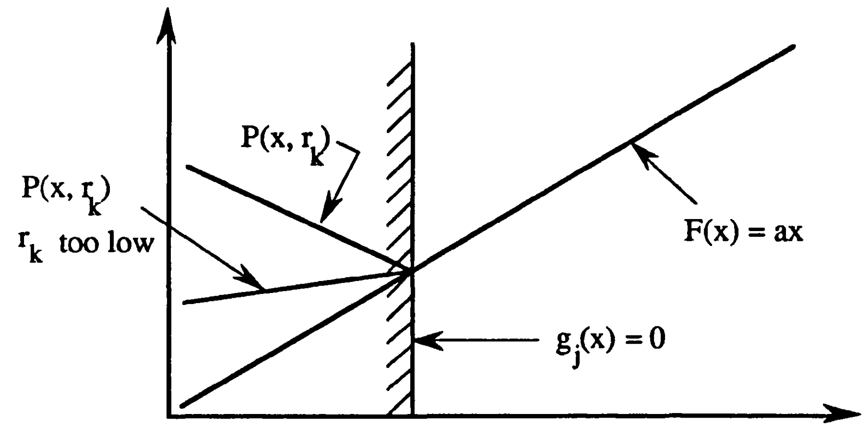
Fig. 13.5 Flow Chart for Hooke and Jeeves Algorithm

13.12, suffer from ill conditioning of the surface $P(\overline{x},r_k)$ due to the discontinuity at the constraint boundary. With this discontinuity, the unconstrained minimisation techniques which depend on the function being reasonably quadratic for best efficiency can be expected to be less effective in external penalty technique problems. On the other hand, those methods which just compare values of the function at points in a prescribed pattern can be fully effective in external penalty technique. This is the reason why the *Hooke* and *Jeeves* direct search and *Nelder* and *Mead* simplex search have been incorporated into the external penalty technique optimisation program.

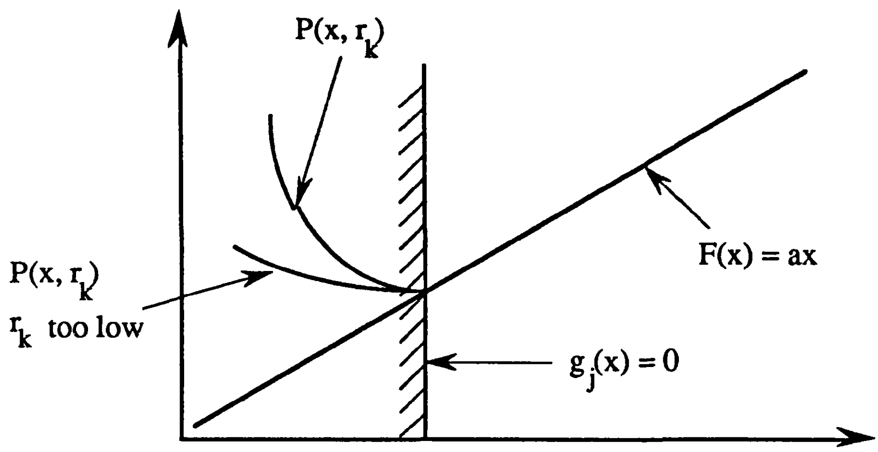
For typical ship design problems where $F(\overline{x})$ is reasonably flat and where the constraints are in the normalised form, r_k equal 1024 has usually been adequate [6]. An excessive value will sharpen the valley in $P(\overline{x},r_k)$ at the constraint boundary and may cause a procedure like *Hooke* and *Jeeves* direct search to be less reliable. If r_k is too low, the solution to the minimisation of $P(\overline{x},r_k)$ can be infeasible. *Wangdahl* [17] proposed a simple procedure to eliminate this problem and is implemented in this study. If at any time during the solution of the unconstrained minimisation of the value of $P(\overline{x},r_k)$ at an infeasible point is lower than found at any previous infeasible point and if the penalty term is larger than at this previous point, the solution may be approaching an infeasible point. If this occurs, the system dynamically double r_k and continues the solution process.

13.3 INTERACTIVE OPTIMISATION DESIGN CONCEPT

The optimum design process requires sophisticated computational algorithms. Since, most algorithms have uncertainties in their computational steps, it is prudent to interactively monitor their progress and guide the optimum design process. Interactive design optimisation algorithms are based on utilising the designer's input during the iterative process. They are in some sense open-ended algorithms in which the designer can specify what needs to be done depending on the current design conditions. They must be implemented into an interactive software having capabilities to interrupt the iterative process and report the status of the design to the user. Various options should be available to the designer to facilitate decision making and change design data. It is possible to restart or terminate the process. With such facilities, designers have complete control over the design optimisation process. They can guide it to obtain better designs and ultimately the best design. Figure 13.7 is a conceptual flow diagram for the interactive design optimisation process. It is a modification of Fig. 13.2, in which an interactive block has been added.



(a) Using Eqn. 13.12



(b) Using Eqn. 13.13

Fig. 13.6 External Penalty Functions

13.3.1 Desired Interactive Capabilities

Interactive software for design optimisation should be flexible and user-friendly. Help facilities should be available in the program which can be menu-driven, command-driven or both. First of all, the program should be able to treat general nonlinear programming as well as constrained problems. It should be able to treat equality, inequality and design variable bound constraints. It should have the choice of a few good algorithms that are robustly implemented. It should trap user's mistakes and not abort abnormally.

13.3.1.1 Interactive Data Preparation

The software should have a module for interactive data preparation and editing. The commands for data entry should be explicit. Only the minimum amount of data should be required. The user should be able to edit any data that have been entered previously. The step-by-step procedures should be to display the menu for data selection and entry, or it should be possible to enter data in a simple question/answer session. The system should be set up in a way so that it is protected from any of the designer's mistakes. If data mismatch is found, messages should be given in detail. The interactive input procedure should be simple so that even a beginner can follow it easily.

13.3.1.2 Interactive Capabilities

As observed earlier, it is prudent to allow designer interaction in the computer-aided design process. Such a dialogue can be very beneficial, saving computer and human resources. All general-purpose design optimisation software needs the following information about the problem to be solved:

a. input data such as number of design variables, number of constraints, etc,

b. the cost and constraint functions, and

c. the gradients of cost and constraint functions.

It is useful to monitor the optimum process by using interactive facility. Histories of the cost function, constraint functions, design variables, maximum constraint violation, and convergence parameter should be monitored. If the design process is not proceeding satisfactorily (should there be inaccuracies or errors in the problem formulation and modelling), it is necessary to terminate it and check the formulation of the problem. This will save human as well as computer resources. Also, if one algorithm is not progressing satisfactorily, a switch should be made to another one. The system should be able to give suggestions for design change based on the analysis of the trends. Therefore, monitoring the iterative process interactively is an important capability that should be available in design optimisation software.

The designer should also be able to guide the problem-solving process. For example, the program can be run for a certain number of iterations and interrupted to see if the process is progressing satisfactorily. It should be possible to change the input data for a design problem during the iterative process. After monitoring the process for a few iterations it may be necessary to change the problem or program parameters. This should be possible without terminating the program.

In short, when the program is run interactively, a wide range of options should be made available for the designer. The following is a list of possible capabilities that can aid the designer in decision-making.

a. The designer may want to re-examine the problem formulation or design data. Thus, it should be possible to exit the program at any iteration.

b. It should be possible at certain iterations to display the status of the design, such as current values of variables, cost function, maximum constraint violation and other such data.

c. It should be possible to change data at certain iterations, such as design variables and their limits, and other relevant data.

d. The designer should be able to run the algorithm one iteration at a time or for several iterations.

e. It should be possible to restart the program from any iteration.

f. It should possible to change the algorithm during the iterative process.

13.4 INTERACTIVE DESIGN OPTIMISATION 'OPTOSVD'

The following section essentially describes specifications for a general purpose interactive design optimisation software. Based on them, a software system can be

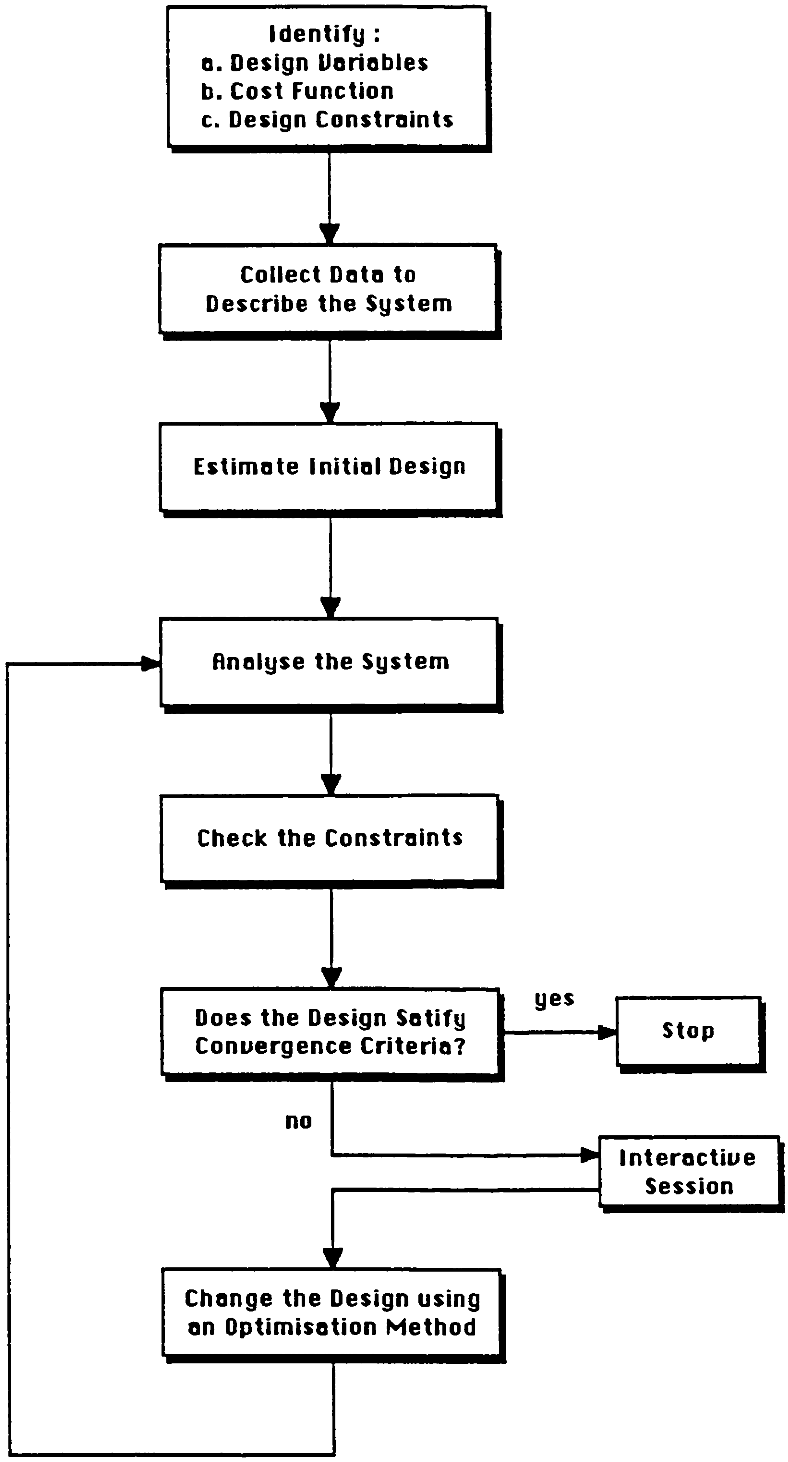


Fig. 13.7 Flowchart for Interactive Optimisation Design

designed and implemented. It can be observed that to implement all the flexibilities and capabilities, the software will be quite large and complex. The most modern software design and data management techniques will have to be utilised to achieve the stated goals. The entire process of software design, implementation and evaluation can be quite costly and time consuming, requiring the equivalent of several man-years.

In this section, a brief description is given of a software OPTOSVD that has some of the previously stated capabilities. OPTOSVD, which stands for Optimisation of Offshore Supply Vessels Design, is a specially written program incorporating expert system *Leonardo* for pure supply vessels or anchor handling/tug/ supply vessels. With the OPTOSVD program, the computer and the designer's experience can be utilised to adjust the design variables so as to improve the design objective while satisfying the constraints. It contains two nonlinear constraint optimisation methods described previously as shown in Fig. 13.8.

OPTOSVD has several facilities that permit the designer to interact with and control the optimisation process. One can backtrack to any previous design or manually input a new trial design. The system has been designed to accommodate both experienced users and beginners. The beginner can respond to one menu at a time as guided on-line instruction. The expert can answer all the menu at once and bypass intermediate menus. The software also identifies and helps the user correct improper responses.

The user will initially be prompted with a selection of type of vessel menu. Once the the type of vessel is selected, the user will be asked to select the goal or objective function of his design. Here, the user is given a choice of selecting one of three objective function that is deadmass, maximum deck cargo or capacity. Along with the objective functions that is highlighted, the numerical equations for the constraints (as given in Table 13.1) is also given. The user will then be asked to input the characteristics of the vessel to be designed in terms of speed and capacity or deadmass.

Once the characteristics of the vessel has been defined, the user will be asked to select the type of optimisation algorithm from either *Hooke* and *Jeeves* or *Nelder* and *Mead*. Depending on the objective function and the type of algorithm selected, the appropriate screen will be highlighted asking the user for the starting values for the variables as well as for its incremental values.

Once the starting values of the variables and its incremental values have been installed, the system will start to execute. While the system is executing a screen will be highlighted to guide the user to press the appropriate key in order to stop the

Table 13.1 Objective Function and Its Constraints

No.	Objective Function	Input Requirements	Design Constraints
1	Deadmass (t) (Dms = LBD/3)	Speed & Capacity	3.75 ≥ L/B ≤ 4.50 2.20 ≥ B/D ≤ 2.70 (1.135 - (V/3.62 * sqrt (L)))) - 0.70 ≥ 0.0 40 * (LBD/100) - Capacity ≥ 0
2	Cargo Deck (t) (CD = L * B)	Speed & Deadmass	3.75 ≥ L/B ≤ 4.50 2.20 ≥ B/D ≤ 2.70 (1.135 - (V/3.62 * sqrt (L)))) - 0.72 ≥ 0.0 (L/6.75 * ((V + 2)/V)^2)^3 - Deadmass ≥ 0.0
3	Capacity (m^3) Cap = 40 * (LBD/100)	Speed, Deadmass & Initial Stability	3.75 ≥ L/B ≤ 4.50 2.20 ≥ B/D ≤ 2.70 (L/6.75 * ((V + 2)/V)^2)^3 - Deadmass ≥ 0.0 (0.001 * L * B) - GM ≥ 0.0

program If such key is pressed, the system will stop executing and an output screen giving the current values of the objective function, variables and the number of iterations done. The user will then be asked whether to continue the program, to change the starting values of the variables or perhaps to change to another algorithm.

The system will continue depending on which phase the user has selected and proceed to optimise the objective function. Having obtained the variables that will give an optimised objective function, the user will then be asked either to continue the system to evaluate detail calculations of the design or to terminate.

Table 13.2 summaries the output of the software OPTOSVD which is executed for several times for different objective functions and different optimisation algorithms.

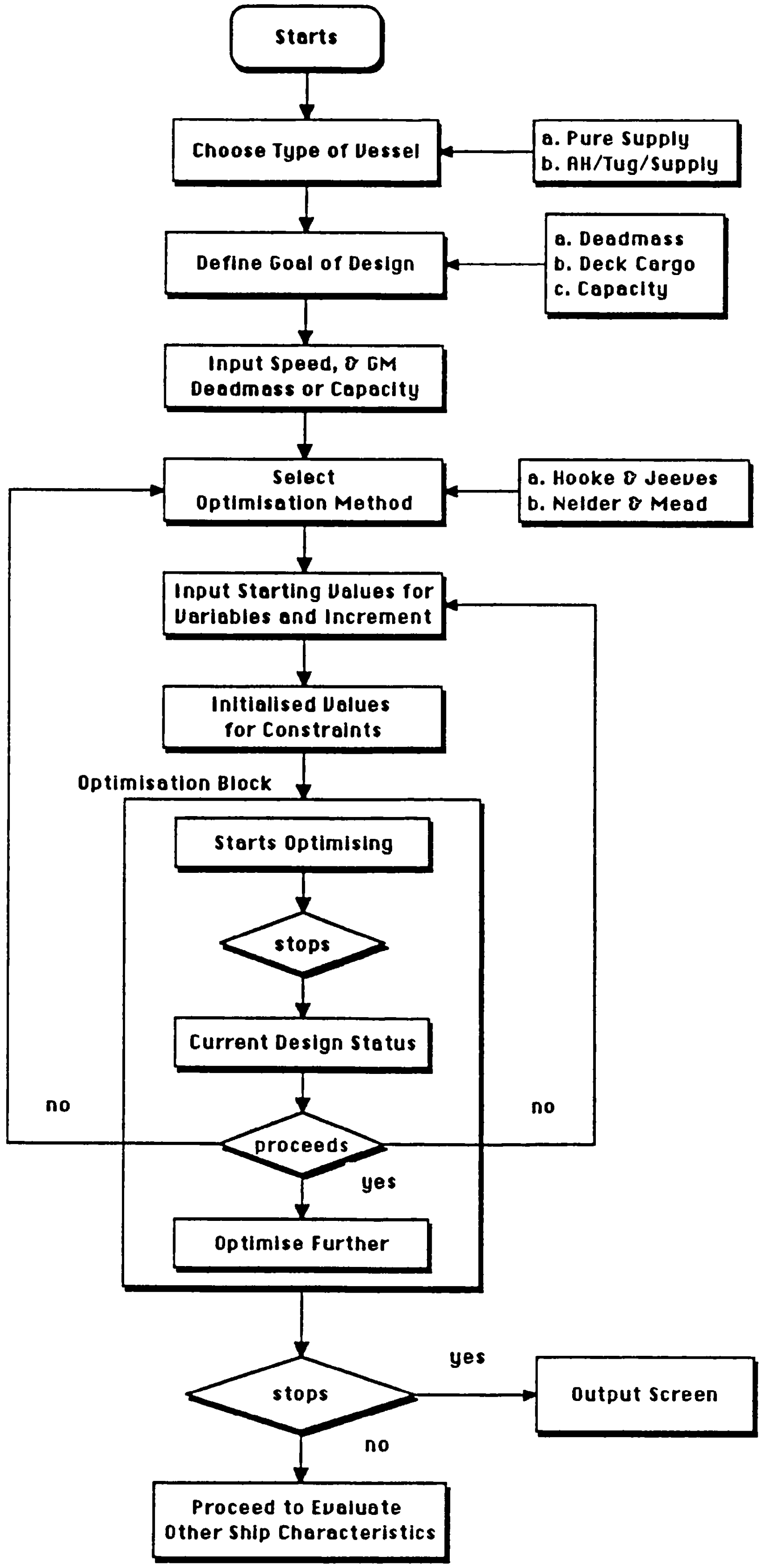


Fig. 13.8 Flowchart for OPTOSVD

Table 13.2 Sample of Results from OPTOSVD

Objective Function	Input Requirement	Method of Optimsation	Starting Values			Ending Values			Value of Objective Function	No. of Evaluation of Objective Function
			L (m)	B (m)	D (m)	L (m)	B (m)	D (m)		
1	V = 11.0 knots C = 1400 m^3	H & J	40.00	10.00	4.00	54.50	12.73	5.05	dms = 1168 t	112
		N & M	40.00	10.00	4.00	56.26	12.62	4.97	dms = 1176 t	198
2	V = 12.3 knots dms = 2400 t	H & J	55.00	12.00	5.30	67.20	15.10	6.42	dc = 1015 t	218
		N & M	55.00	12.00	5.30	68.80	14.78	6.19	dc = 1017 t	304
3	V = 14.0 knots GM = 1.0 m dms = 3000 t	H & J	65.00	12.50	6.00	74.53	16.86	7.05	C = 3544 m^3	136
		N & M	65.00	12.50	6.00	73.11	17.05	6.98	C = 3480 m^3	105

13.5 CONCLUSION

This chapter has described an iteractive preliminary design process of offshore supply vessels which makes use of optimisation techniques, but which also draws on established theory and rule-based structures.

The method illustrates that the optimisation concept could be applied to preliminary ship design, given a suitable objective, constraint and a set of variables to manipulate. The objective function and constraints chosen in this studies are made simple but could be extended for a quite complex problem. However, the aim of the study in to develop an optimisation system which could be interactive and user friendly.

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CHAPTER 14

PARAMETRIC STUDIES OF OFFSHORE SUPPLY VESSELS

CHAPTER 14

PARAMETRIC STUDIES OF OFFSHORE SUPPLY VESSELS

14.0 INTRODUCTION

Preliminary ship design requires making a large number of assumptions when going through its different stages. In the previous chapters, the various computer subprograms were described together with methods employed, assumptions made regarding some of the variables and then testing and validations. Acceptability or success of the whole procedure depends upon accuracy of these assumptions. Therefore, it is necessary to know to what extent the design is affected by these assumptions and see how it varies in response to changes made on them. In parametric studies, changes are made in the design parameters to cover a sensible range and actual designs can be expected to be within the range studied.

In this section, parametric studies of offshore supply vessels will be considered in two separate ways. The first case assumed that the owner would charter the vessel. Thus in this case, the minimum charter rate is taken as the measure of merit. The second case assumed that the owner himself will be operating the vessel, so the exclusion of fuel cost when chartered and its inclusion when owned. Inflation may need to be considered when comparing charter rates (day rates).

14.1 OWNER CHARTERING THE VESSEL

In this section, the main parameters of the offshore supply vessels are varied in order to study the effect of such changes on the minimum charter rate. The minimum charter rate is defined as the least value that the owner is able to charter the vessel in order to balance its building and operating accounts. The vessel is assumed to be ready for delivery in one and half years and has an operating life of 15 years. Other important data is given in Table 14.1. Since fuel cost is excluded, the study mainly shows the variation in capital cost including machinery resulting from a range of vessel geometry. In all cases, capacity is adequate for the given deadmass.

Parametric studies have been carried out to produce a variation of deadmass, block coefficient, speed and length. Deadmass from 800 tonnes to 3600 tonnes, block coefficient from 0.73 to 0.79, and speed from 10 knots to 16 knots have been investigated. For each value of deadmass, block coefficient and speed, a methodical variation was carried out on the parameters L/B and B/T ratios. A diagrammatic illustration of the methodical variation is given in Fig. 14.1.

Table 14.1 Assumptions Taken for Parametric Studies
(Owner Chartering the Vessel)

No.	Item	Value
1	Number of Crew	12
2	Number of Days Chartered per Year	340
3	Interest Rate on Loan	8%
4	Loan Period	8 years
5	Present Worth Factor	10%
6	Depreciation Type	Free
7	Tax Rate	35%

14.1.1 Deadmass Variation Series

A deadmass series was produced by carrying out methodical variation of L/B and B/T ratios for a number of deadmasses. The deadmass was stepped from 800 tonnes to 3600 tonnes in steps of 400 tonnes, upon which was placed a tolerance of ± 25 tonnes. For each value of deadmass, 12 designs were produced, by variation of L/B and B/T from 3.5 to 5.0 and 2.2 to 3.0 respectively. The block coefficient was 0.75 and speed remained at 12 knots.

The results of the deadmass variation series have been plotted to show how the minimum charter rate for the vessel varies with L/B and for B/T for fixed deadmass

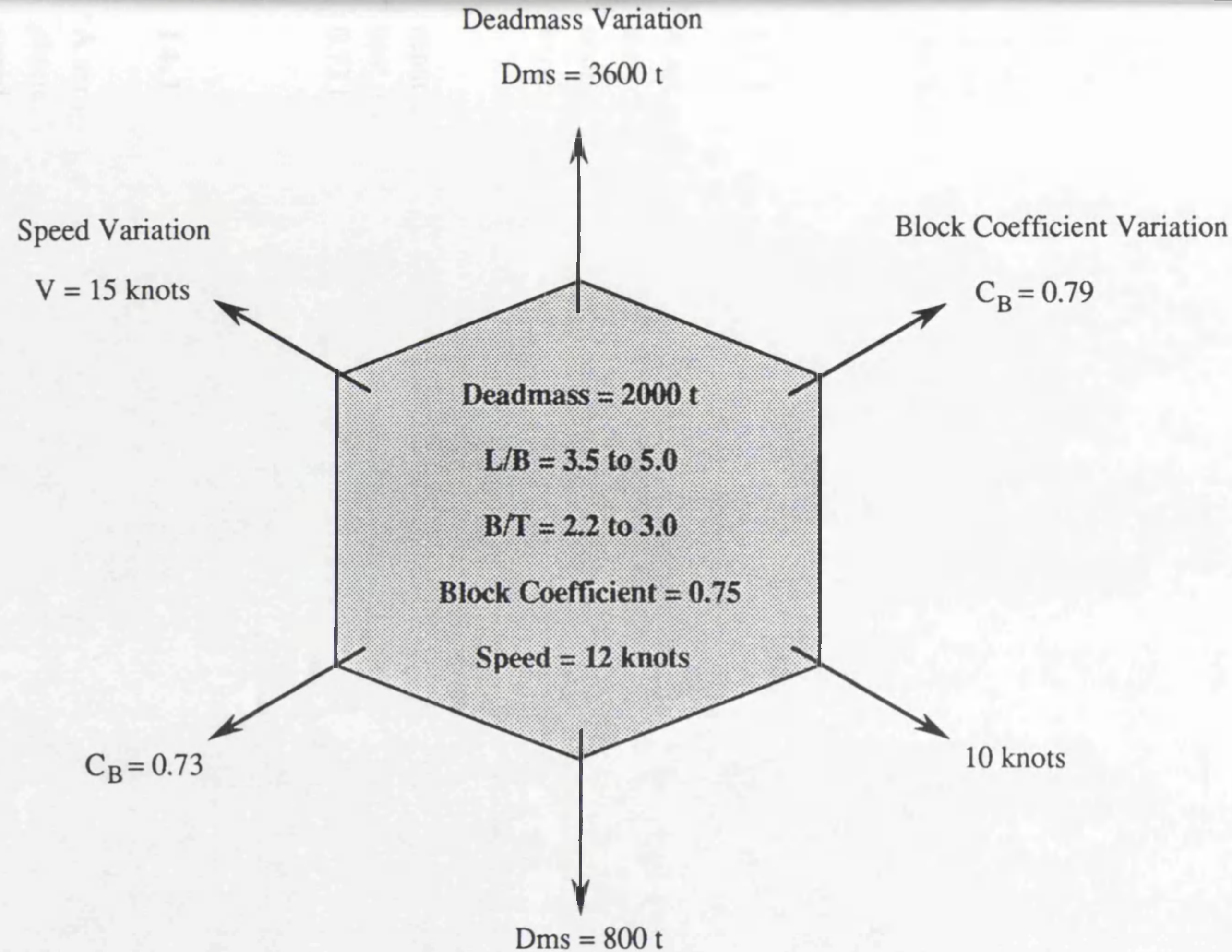

Fig. 14.1 Schematic Diagram for Systematic Parametric Studies

as given in Figs. 14.2 to 14.9. Lines of constant length of vessel are drawn for guidance and for *Froude* number.

From Fig. 14.2 to Fig. 14.9, there is only modest variation in the minimum charter rate from the best to the worst with 2% being an average. In all cases, the lowest length/beam ratio associated with the highest beam/draught ratio , together with the lowest *Froude* number gives the best results. The program ensures that capacity requirement are met. At all points away from this minimum the vessel is becoming larger than required and any compensating benefits of improved specific resistance on machineries cannot reverse the trend.

14.1.2 Block Coefficient Variation Series

A series of designs has been produced to investigate the effect of block coefficient on the minimum charter rate for constant deadmass. The range of block coefficients considered were from 0.73 to 0.79 for a deadmass of 2000 tonnes and a speed of 12 knots.

Figures 14.10 to 14.13 shows the results. A small percentage of about 2.6% separates the best results from the worst but the influence of block coefficient on the best results is negligible over the range considered and the smallest block coefficient of 0.73 has no advantage.

14.1.3 Speed Variation Series

A series of designs has been produced to show the effect of speed on the minimum charter rate. Curves have been drawn for fixed B/T ratios with contours of constant speed on a base of L/B as shown in Figs. 14.14 to 14.17.

The results show that the lowest speed is always best. This is unsurprising as higher speed adds to capital cost and its advantage in carrying more goods is not part of the owner balance sheet.

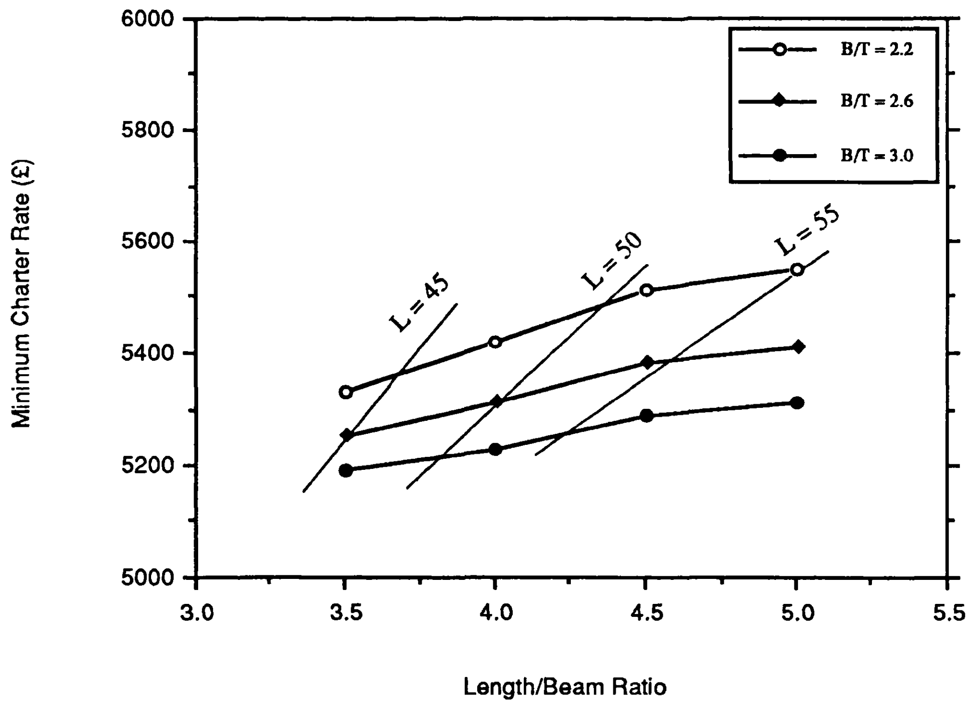

Fig. 14.2 Deadmass Variation Series - 800 tonnes

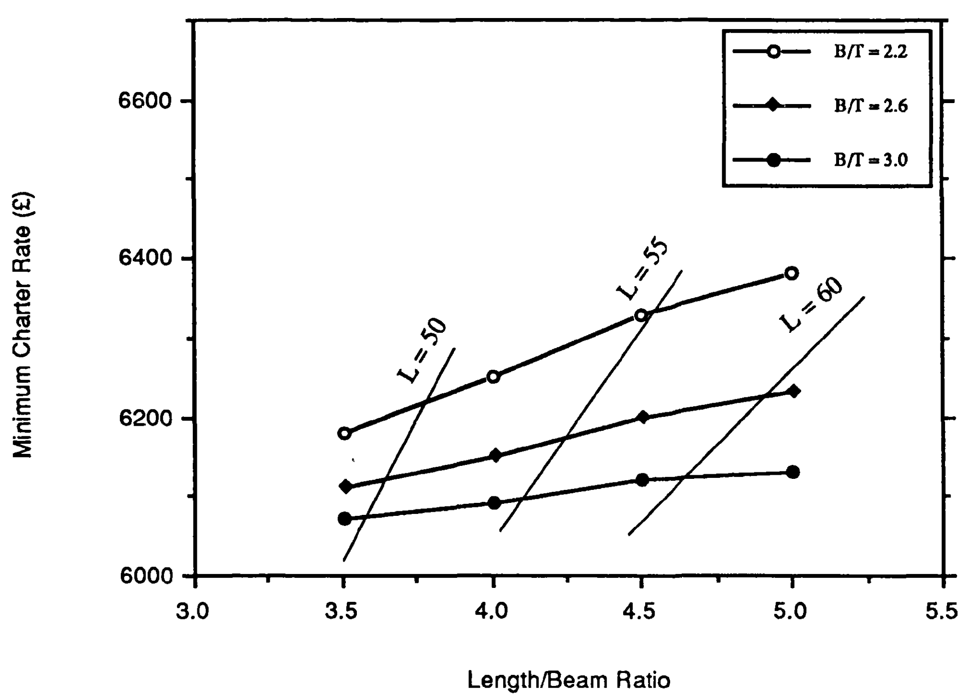

Fig. 14.3 Deadmass Variation Series - 1200 tonnes

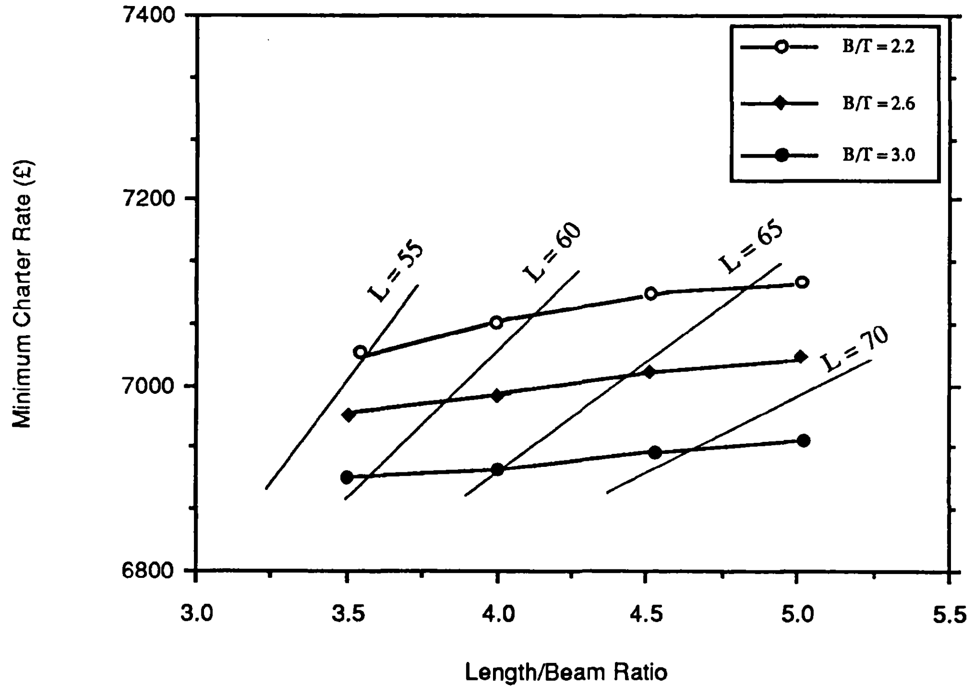

Fig. 14.4 Deadmass Variation Series - 1600 tonnes

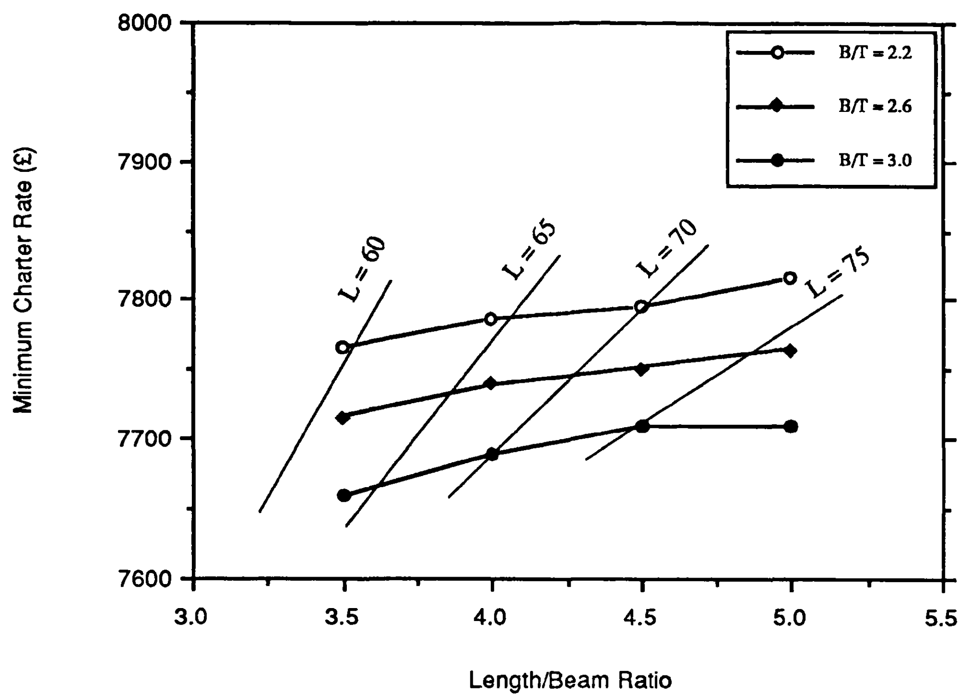

Fig. 14.5 Deadmass Variation Series - 2000 tonnes

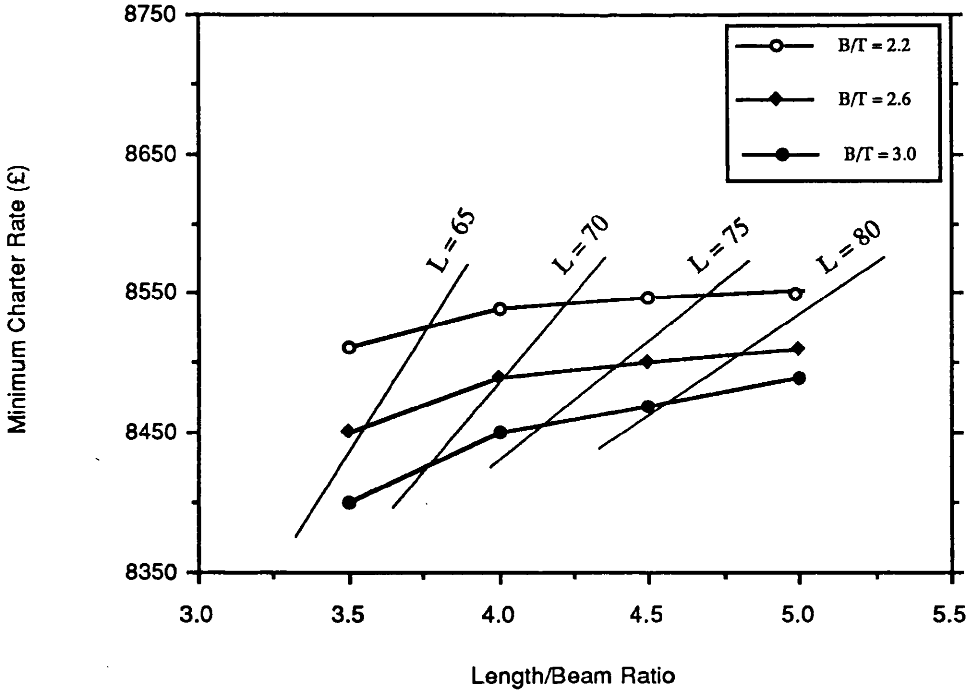

Fig. 14.6 Deadmass Variation Series - 2400 tonnes

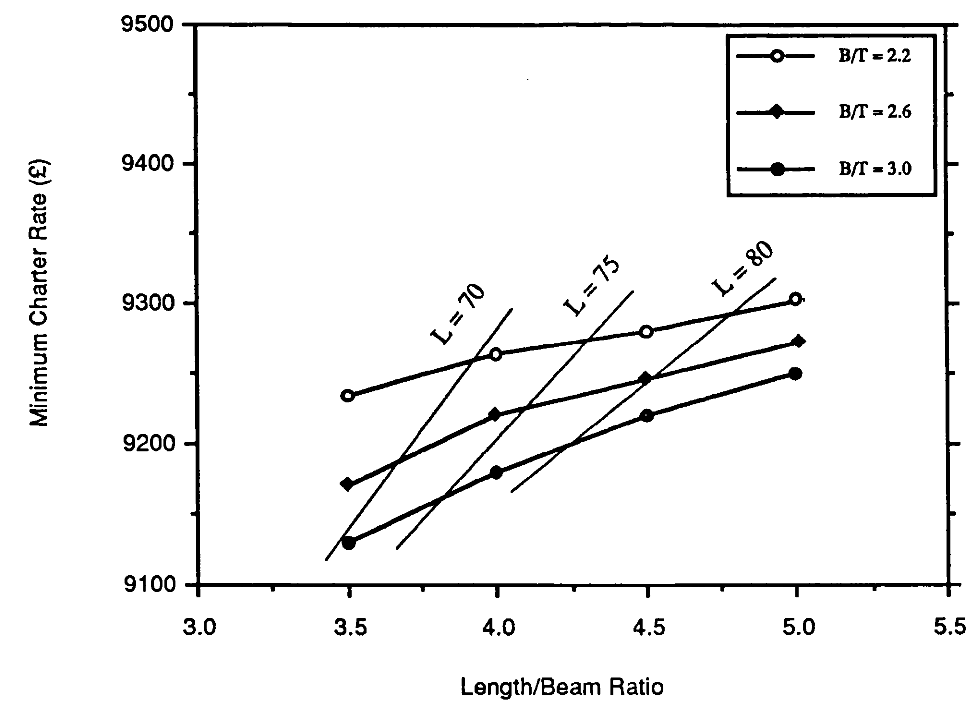

Fig. 14.7 Deadmass Variation Series - 2800 tonnes

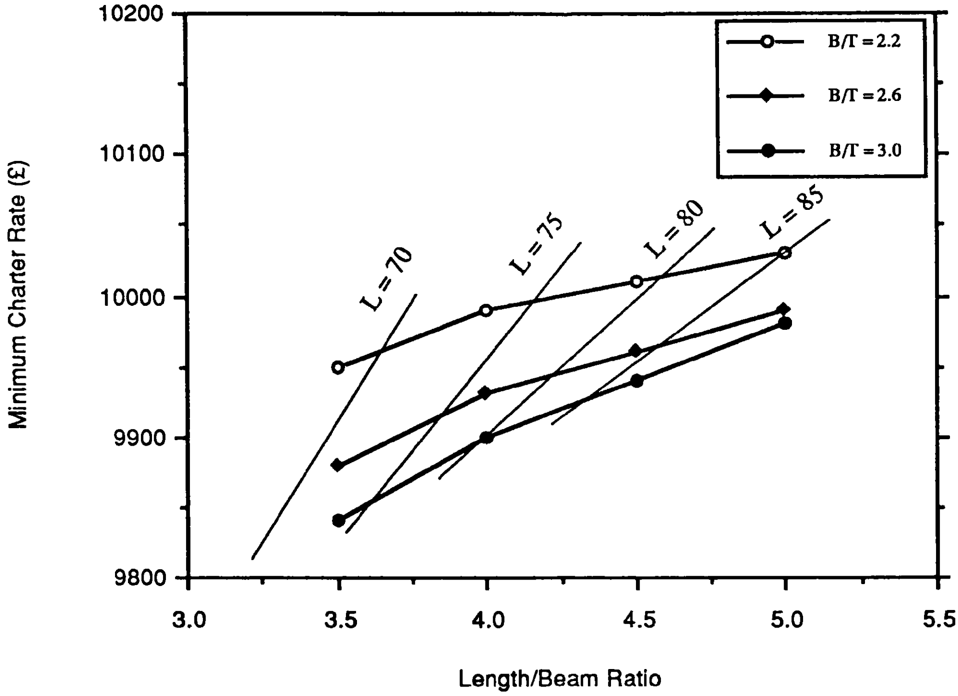

Fig. 14.8 Deadmass Variation Series - 3200 tonnes

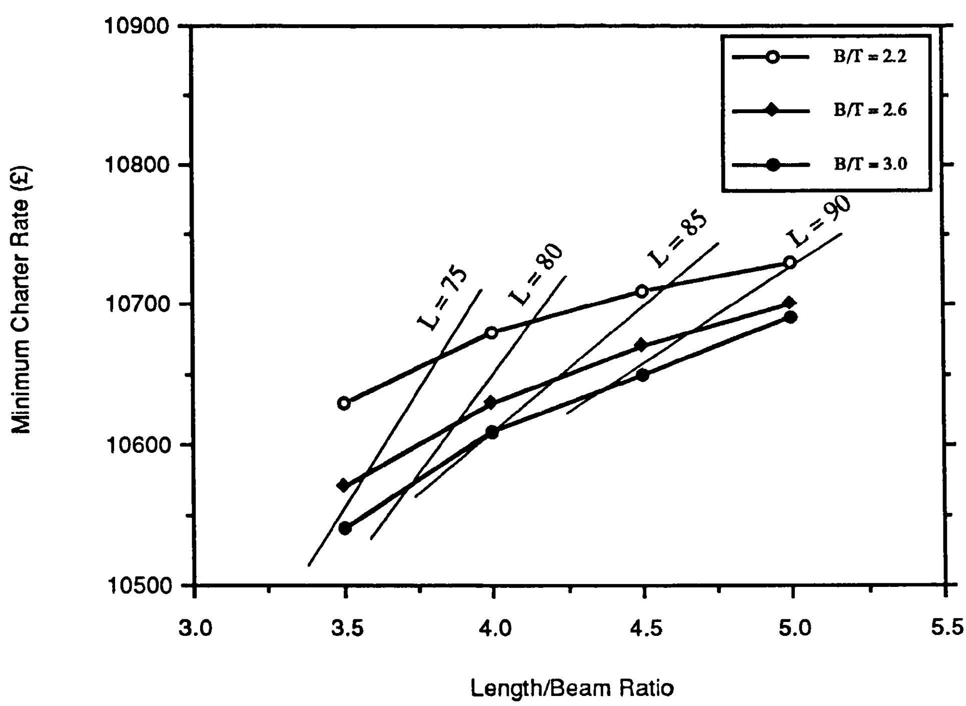

Fig. 14.9 Deadmass Variation Series - 3600 tonnes

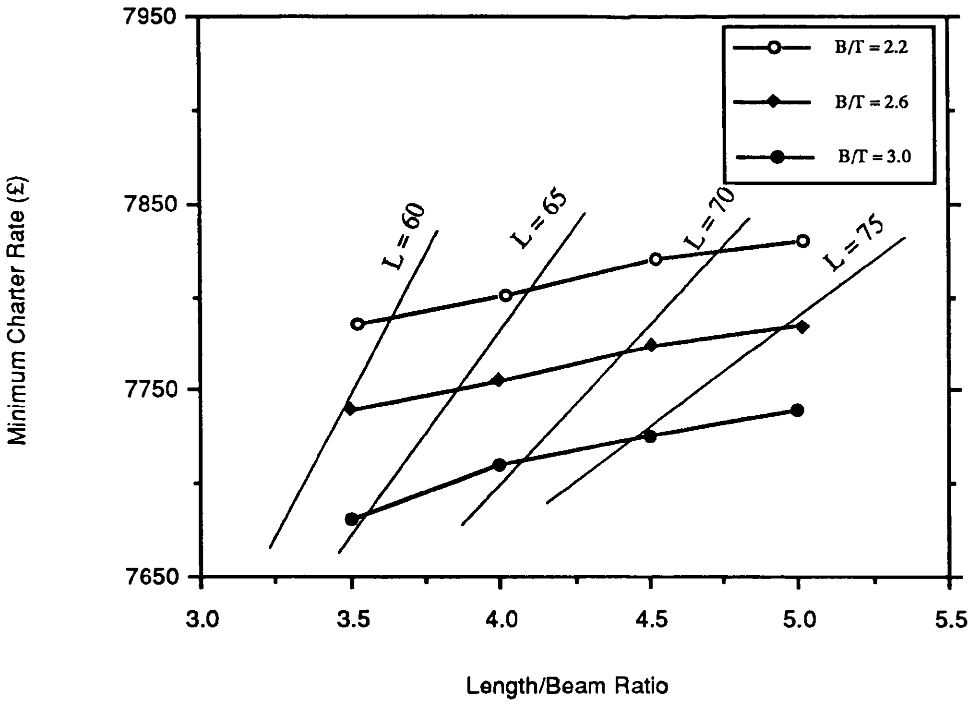

Fig. 14. 10 Block Coefficient Variation Series - 0.73

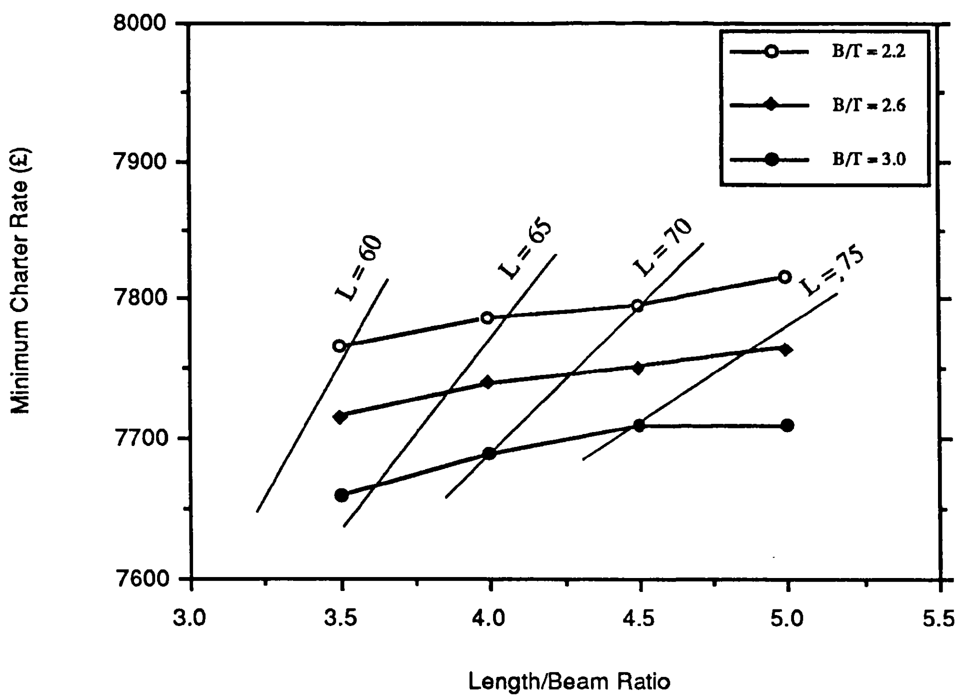

Fig. 14. 11 Block Coefficient Variation Series - 0.75

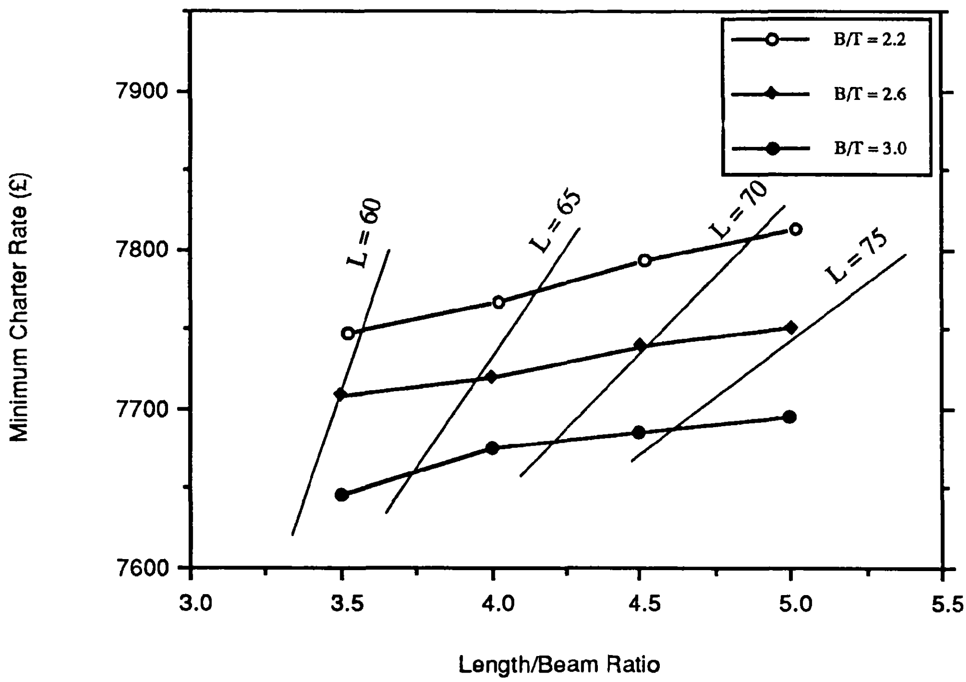

Fig. 14.12 Block Coefficient Variation Series - 0.77

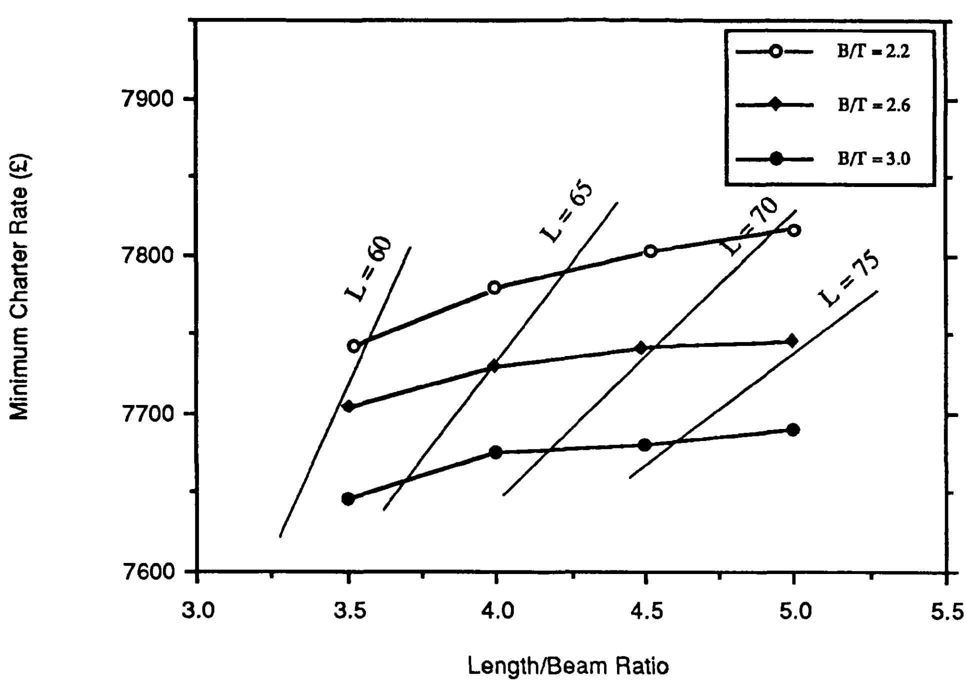

Fig. 14.13 Block Coefficient Variation Series - 0.79

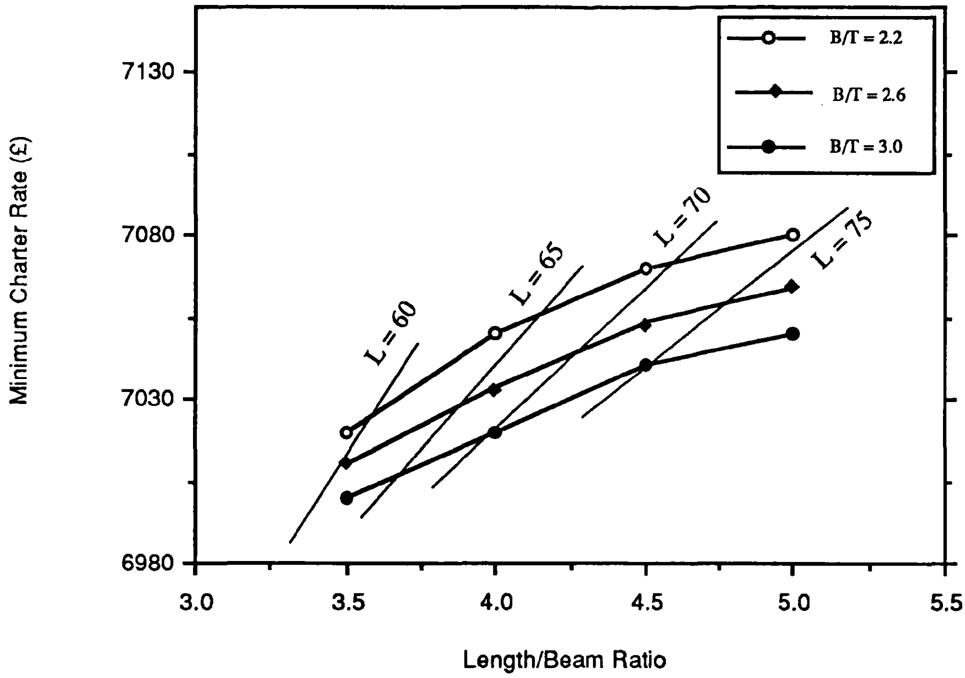

Fig. 14.14 Speed Variation Series - 10 knots

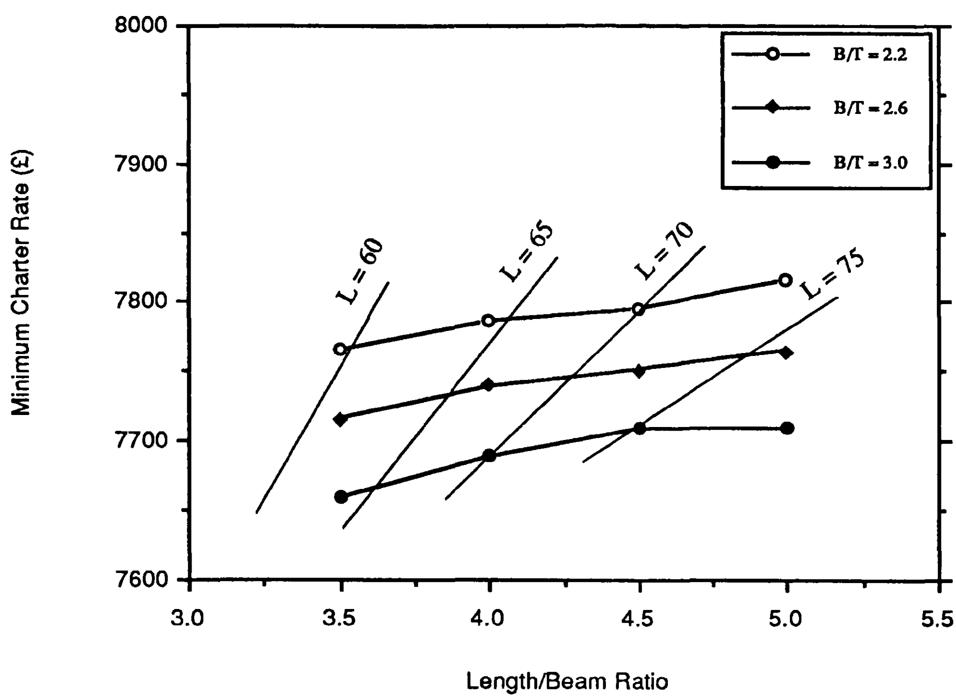

Fig. 14. 15 Speed Variation Series - 12 knots

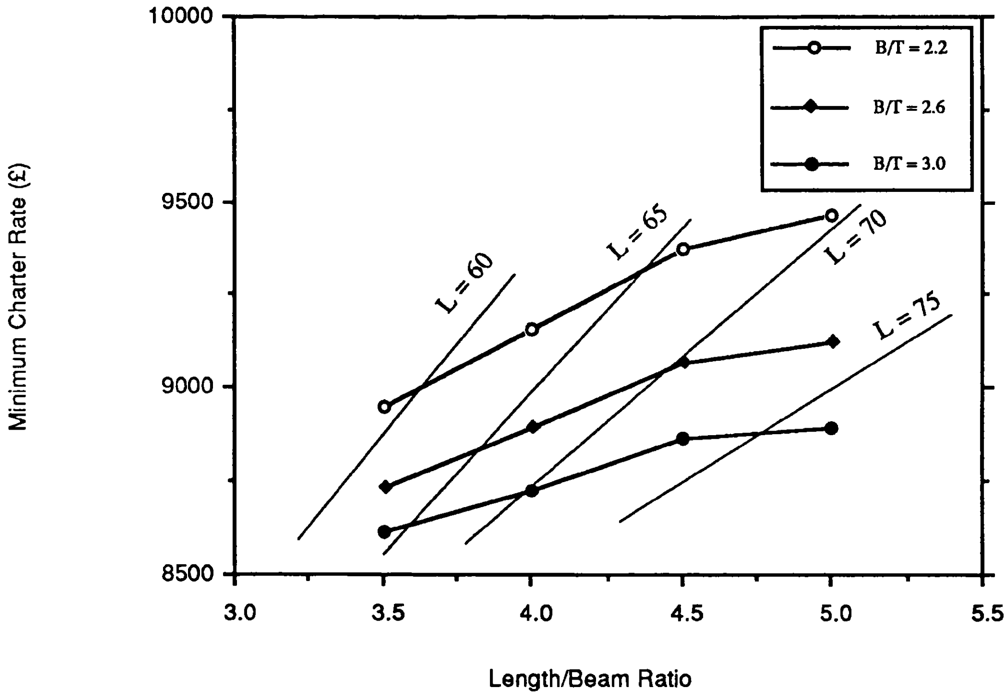

Fig. 14.16 Speed Variation Series - 14 knots

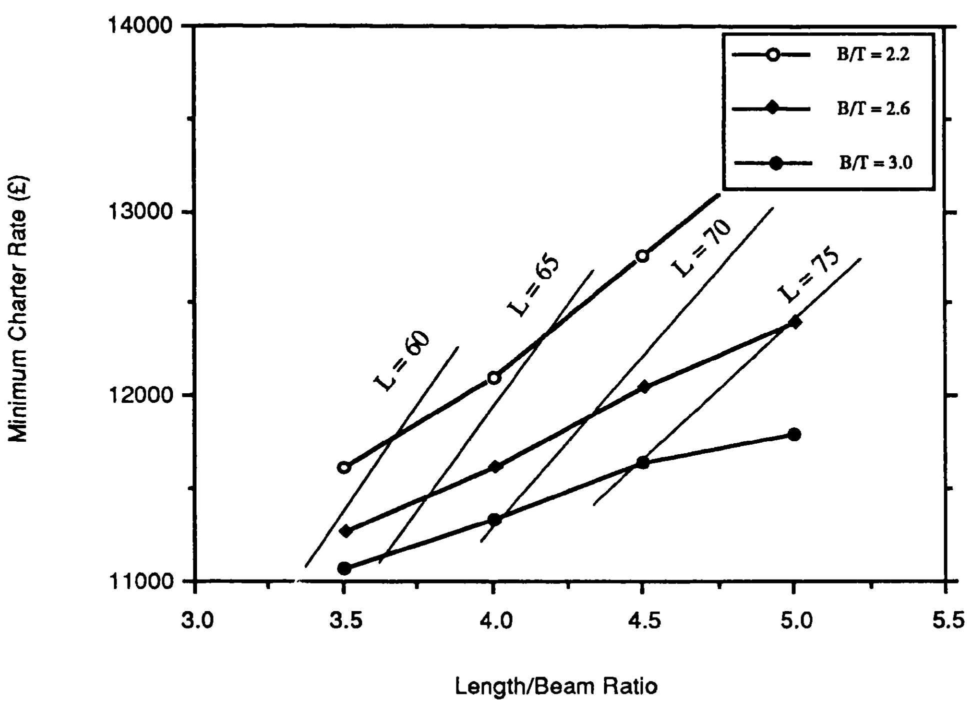

Fig. 14.17 Speed Variation Series - 16 knots

14.1.4 Length Variation Series

A series of designs has been produced by varying the length from 50 metres to 70 metres whilst maintaining a constant beam of 13.40 metres and draught of 4.9 metres. A beam of 13.40 metres is selected because it is the minimum to provide room for for four containers abreast. Four series were produced for block coefficients of 0.73, 0.75, 0.77 and 0.79.

The minimum charter rate has been plotted on a base of deadmass producing a surface with contours of length and block coefficient as shown in Fig. 14.18. The overall change of charter rate is about 12% but it steadily rises with deadmass and block coefficient.

14.2 OWNER OPERATING THE VESSEL

In this section investigation is done on the basis that the owner will be operating the vessel. Thus, the fuel cost, cargo handling cost, port charges are included in the operating cost and the required freight rate (£/tonnes) is used as a measure of merit. The fuel cost, cargo handling cost and port charges are evaluated using the equations given in Chapter 7. Apart from the assumptions given in Table 14.1, additional assumptions taken are given in Table 14.2.

Table 14.2 Further Assumptions Taken for Parametric Studies
(Owner Operating the Vessel)

No.	Item	Value
1	Distance of Rig from Supply Base	250 km (135 nm)
2	Time for Loading Material	10 hrs
3	Time for Unloading Material	14 hrs
4	Time Delayed due to Weather, etc	6 hrs

* 1 kilometre = 0.54 nautical miles

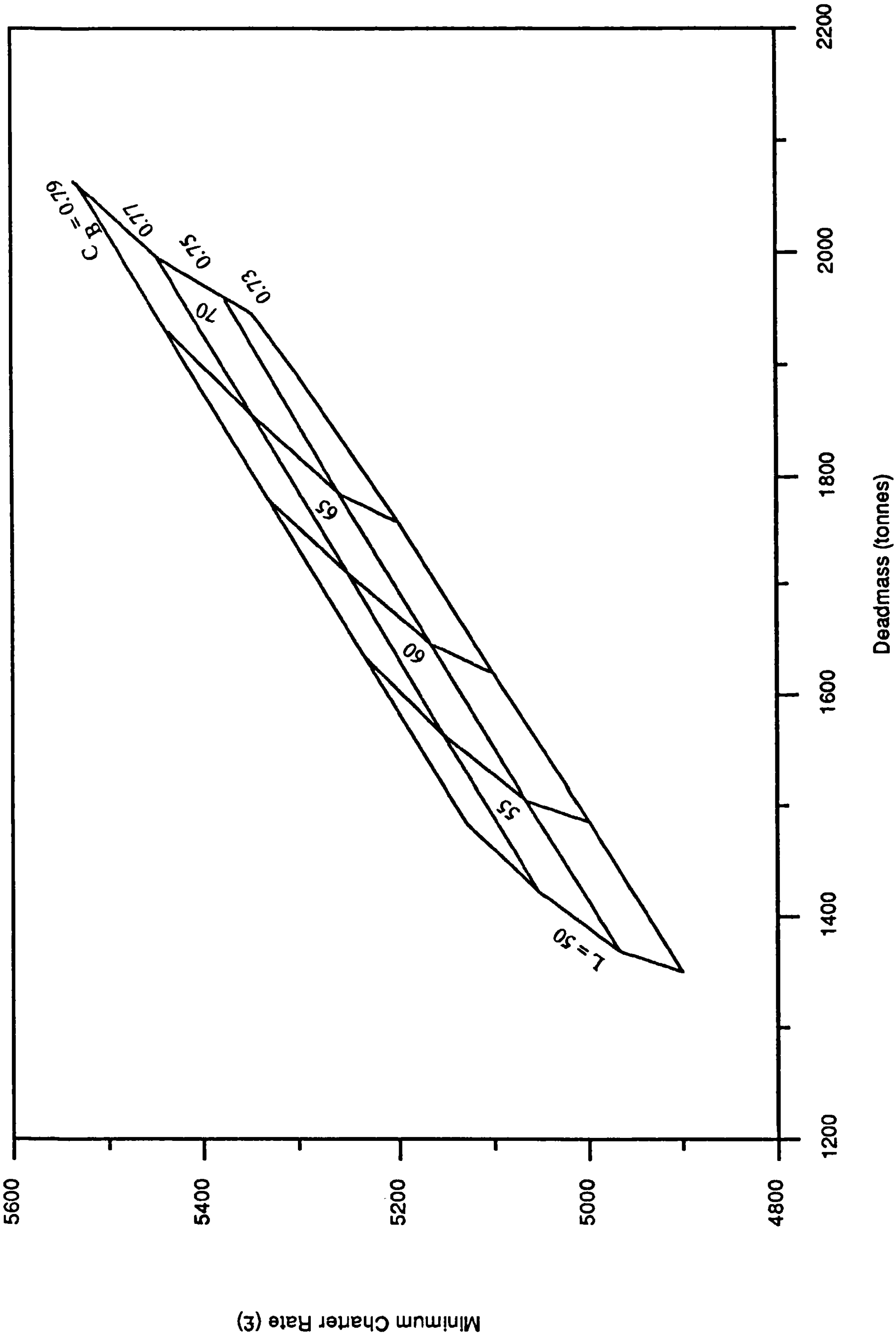

Fig. 14.18 Minimum Charter Rate Against Deadmass and Length

14.2.1 Deadmass versus Required Freight Rate

A series of designs have been produced by varying the deadmass from 800 tonnes to 3200 tonnes at interval of 800 tonnes and at speed of 10 knots to 16 knots at interval of 2 knots, while the block coefficient remains at 0.75. For each set of deadmass and speed, 16 designs were produced at constant length/ beam ratio and beam/draught ratios. The length/ beam ratio increases from 3.5 to 5.0 while the beam/ draught ratio increases from 2.2 to 3.0. the results are shown in Figs. 14.19 to 14.26.

The plots shows the economies of greater size and the general disadvantage of greater speed which within the range considered is never counterbalanced by carrying more cargo. The required freight rate ranges from about 8 to 48 £/tonne and obviously many of the designs would be quite uneconomic.

14.2.2 Effect of Shipbuilding Cost

A series of designs is produced to investigate the effect of shipbuilding cost on the required freight rate. The cost is increased successively by 25% and 50% and reduced by 25% with length/beam ratio is 4.0 and beam/draught ratio is 2.2.

Figure 14.27 shows the advantage of lower shipbuilding cost although the gain diminishes as size increases.

14.2.3 Effect of Distance Travelled

A series of designs is produced to investigate the effect of distance travelled on the required freight rate. The distance is increased successively to 350 and 450 km and reduced to 150 km. The characteristics of the vessels such as length/beam ratio and beam/draught ratio remains at 4.0 and 2.2 respectively. The speed of the vessel remains at 12 knots.

From Fig. 14.28, the required freight rate increases as the distance travelled

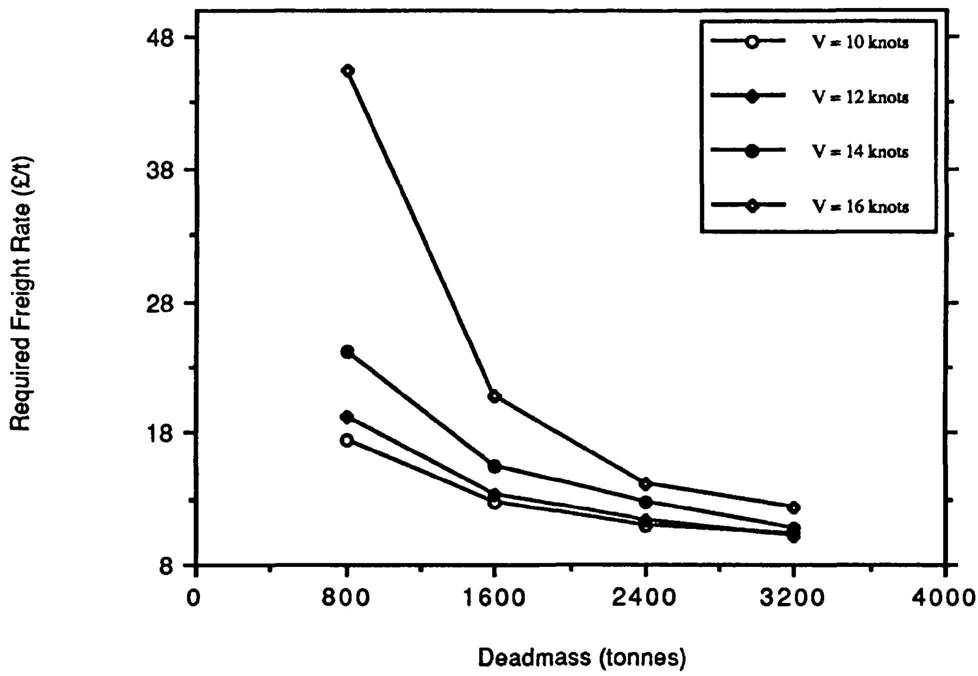

Fig. 14.19 RFR versus Deadmass - (L/B = 3.5, B/T = 2.2)

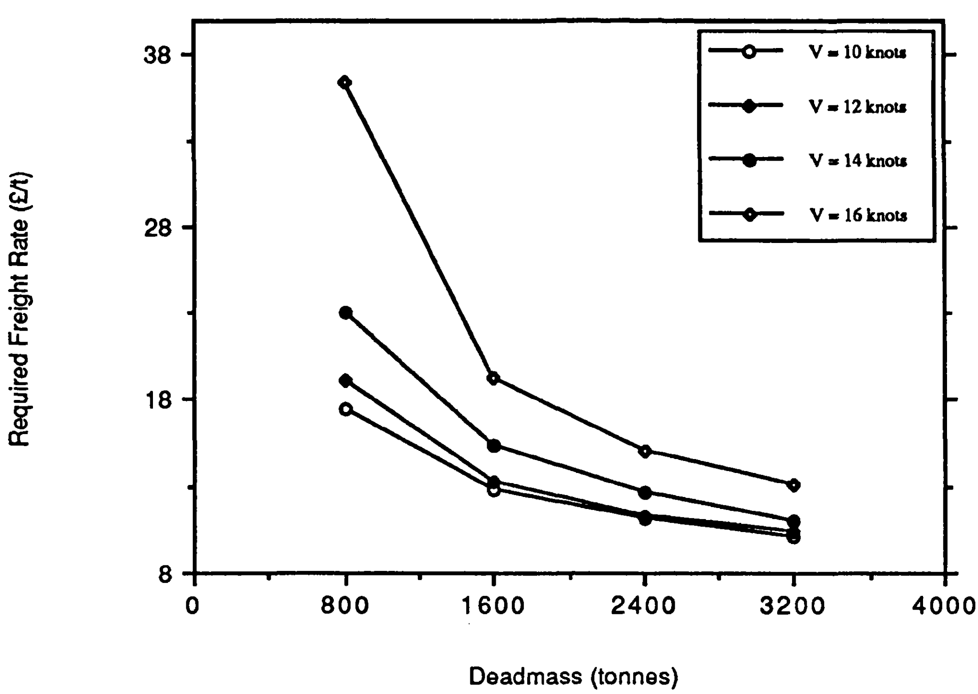

Fig. 14.20 RFR versus Deadmass - (L/B = 4.0, B/T = 2.2)

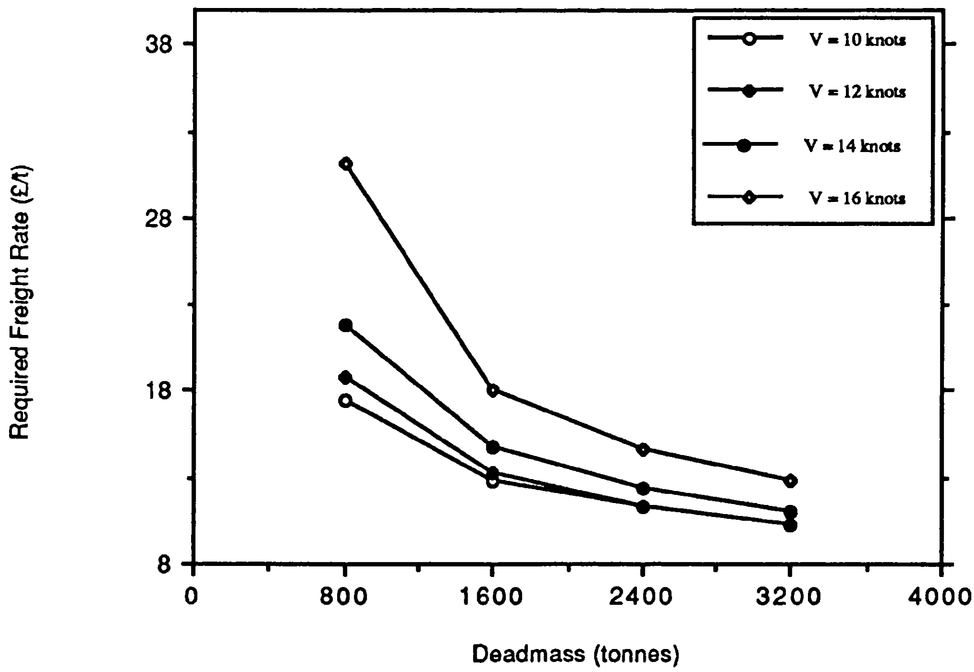

Fig. 14.21 RFR versus Deadmass - (L/B = 4.5, B/T = 2.2)

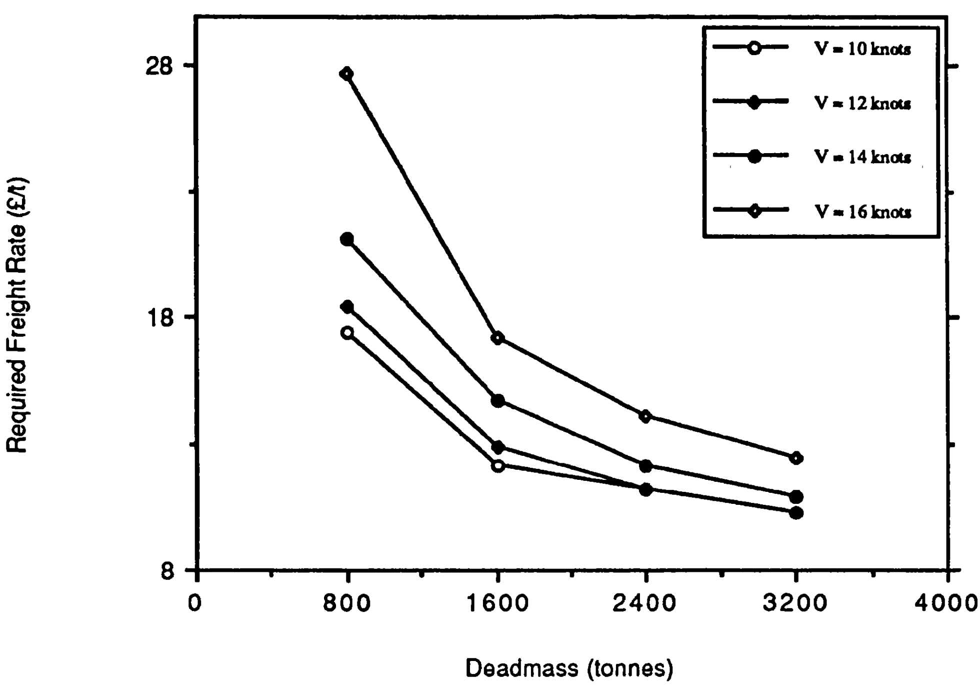

Fig. 14.22 RFR versus Deadmass - (L/B = 5.0, B/T = 2.2)

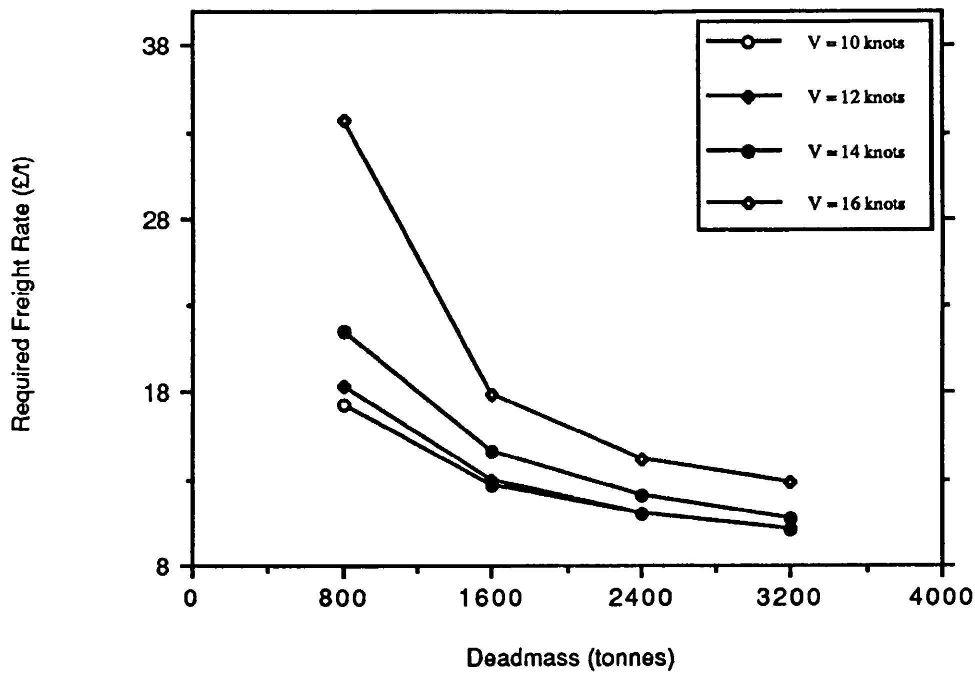

Fig. 14.23 RFR versus Deadmass - (L/B = 3.5, B/T = 3.0)

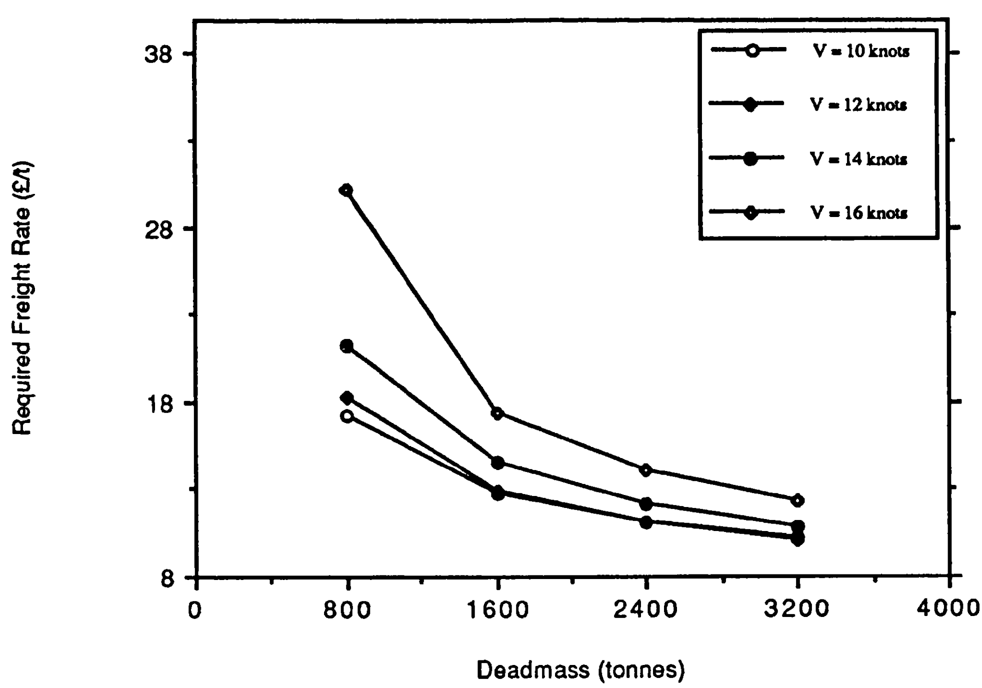

Fig. 14.24 RFR versus Deadmass - (L/B = 4.0, B/T = 3.0)

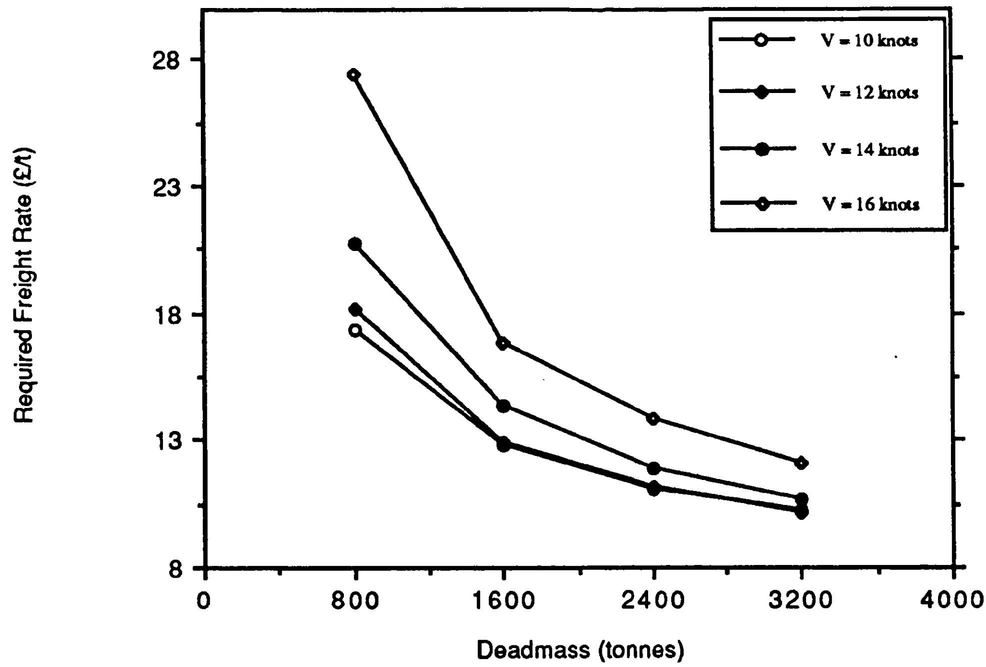

Fig. 14.25 RFR versus Deadmass - (L/B = 4.5, B/T = 3.0)

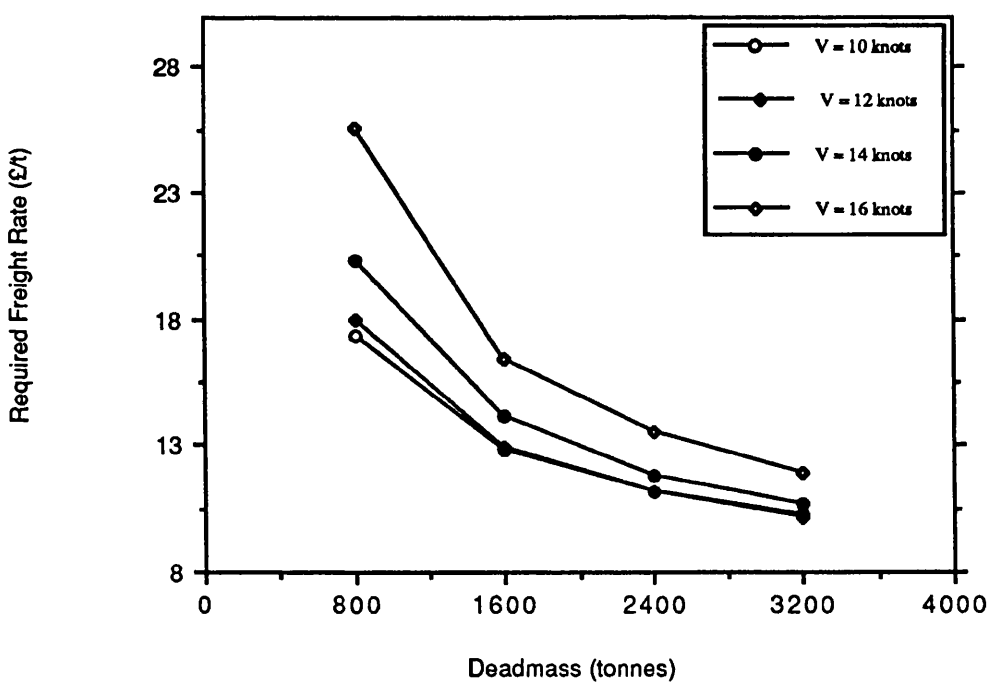

Fig. 14.26 RFR versus Deadmass - (L/B = 5.0, B/T = 3.0)

increased. This is expected since the longer the distance travelled, the more fuel is being used by the vessel but the economies of scale show to the advantage of the larger vessel.

14.2.4 Effect of Fuel Cost

The effect of fuel cost on the required freight rate is next to be investigated. In this study, the fuel cost is increased by 25 and 50% and reduced by 25%. The speed, length/beam ratio, beam/draught ratio remains at 12 knots, 4.0 and 2.2 respectively.

From Fig. 14.29, the effect of fuel cost on the required freight rate is very small.

14.2.5 Effect of Number of Crew

In the basis example, the number of crew considered is 12. A series of designs is produced with number of crew of 8, 10 and 14. From Fig. 14.30, the effect of the number of crew on the required freight rate is not significant.

14.3 CONCLUSION

This chapter illustrates some of the parameters of the offshore supply vessels which are influential with regard to the minimum charter rate or the required freight rate. It can be argued that the minimum charter rate is of little value, ignoring as it does fuel costs, but no vessel will obtain a charter if the fuel consumption is above normal. An excess of power even if it is never used seems an attraction in practice.

Not surprisingly, the most economical vessels turn out to be of least size to meet the deadmass and associated capacity requirements and travel at low speed. However, the real market is likely to reward the ability to travel relatively fast when required even though this may slightly affect the required freight rate. For example, a vessel having a design speed of 16 knots but operating at 14 knots would increased the required freight rate by 1.6 £/tonne.

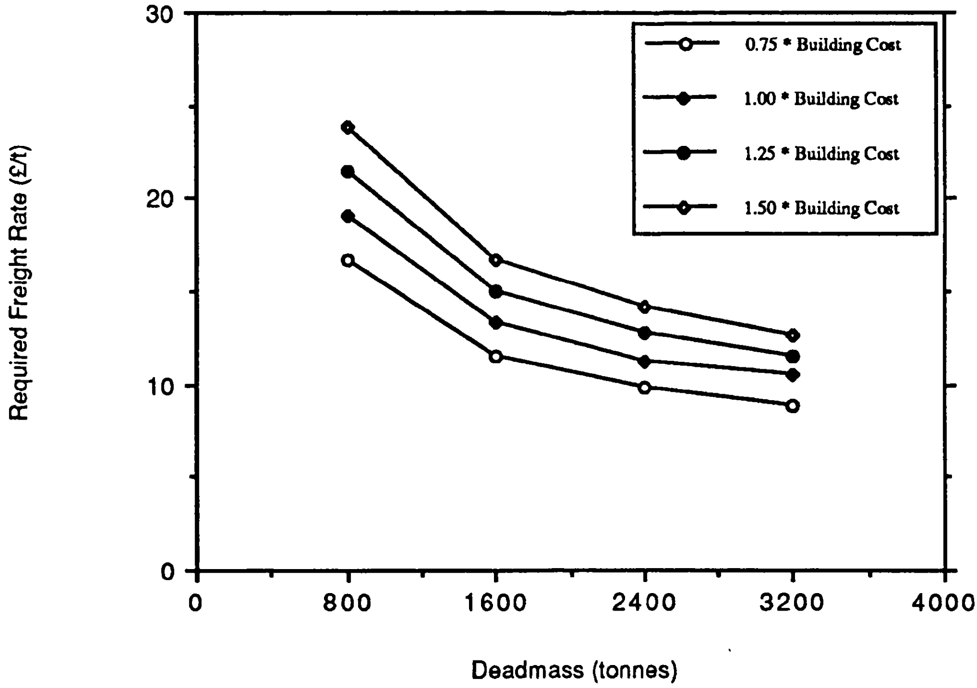

Fig. 14. 27 Effect of Shipbuilding Cost on RFR

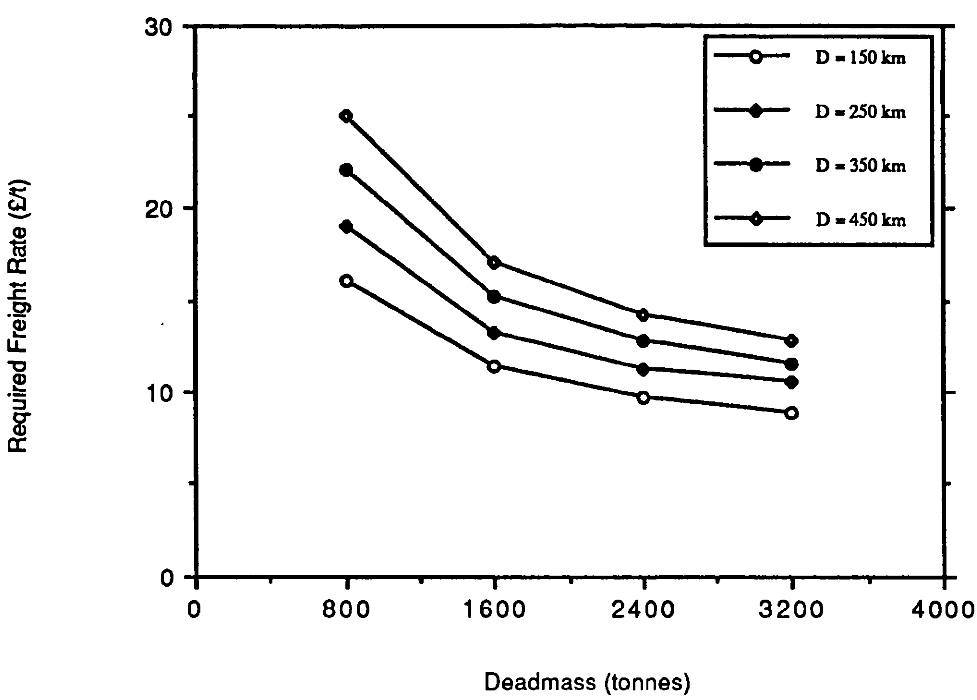

Fig. 14.28 Effect of Route Distance on RFR

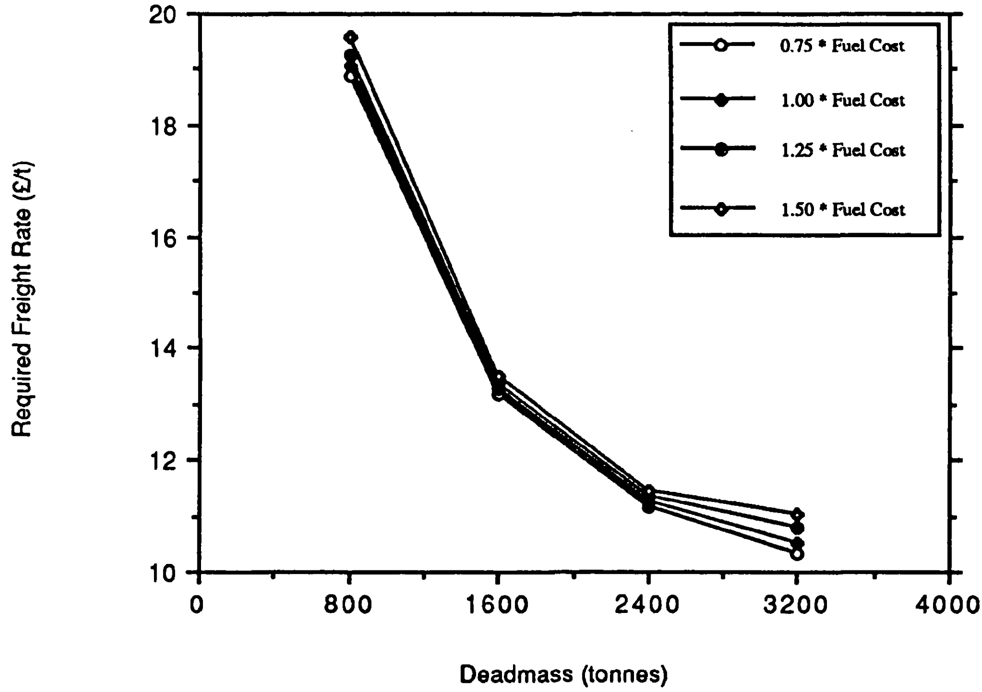

Fig. 14.29 Effect of Fuel Cost on RFR

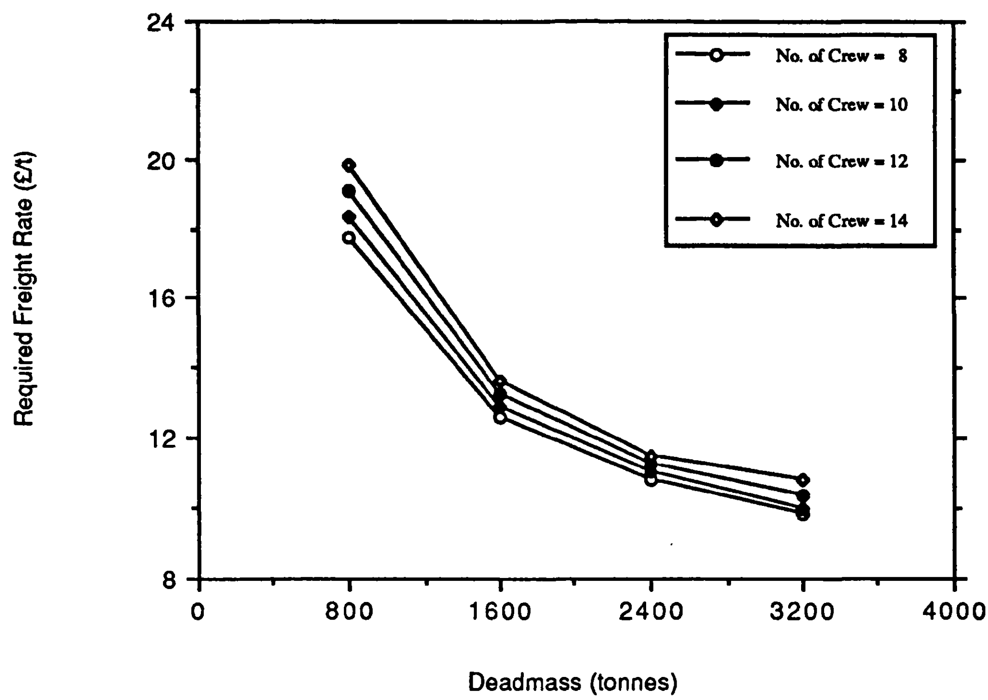

Fig. 14.30 Effect of Crew Number on RFR

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CHAPTER 15

METHODS OF INCORPORATING UNCERTAINTY IN THE PRELIMINARY DESIGN OF OFFSHORE SUPPLY VESSELS

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15.0 INTRODUCTION

Preliminary ship design requires making a large number of assumptions when going through its different stages. Acceptability or success of the whole procedure depends upon accuracy of these assumptions. It is therefore necessary to know to what extent the design is affected by these assumptions and to observe how it varies in response to changes made on them. Designs have to operate during their life in environments and market that can, at best, be only guessed at and there is the possibility of a fair amount of variability in them. The estimation of the main ship characteristics such as masses and costs are traditionally based on historical data which could be the source of uncertainties. In any case, many estimates are based on regression of historical data. As regression involves fitting some logical mathematical expression to data, the scatter in and the incompleteness of the data inevitably means that the fit is hardly ever exact, and again this introduce some uncertainty. How the uncertainties in individual ship design calculations affect the overall uncertainty can be schematically visualised as shown in Fig. 15.1.

Thus, potential inherent uncertainty in each of the items is influenced further by the uncertainties in other items. If the uncertainty could be quantified so that the range and likelihood of different values for item such as ship cost, the operators and designers could quote the expected figure with greater certainty.

15.1 NATURE OF UNCERTAINTIES IN PRELIMINARY SHIP DESIGN

According to MacCallum [5], there are three different areas of uncertainty in the design process associated with :

a. the specification of objectives or goals,

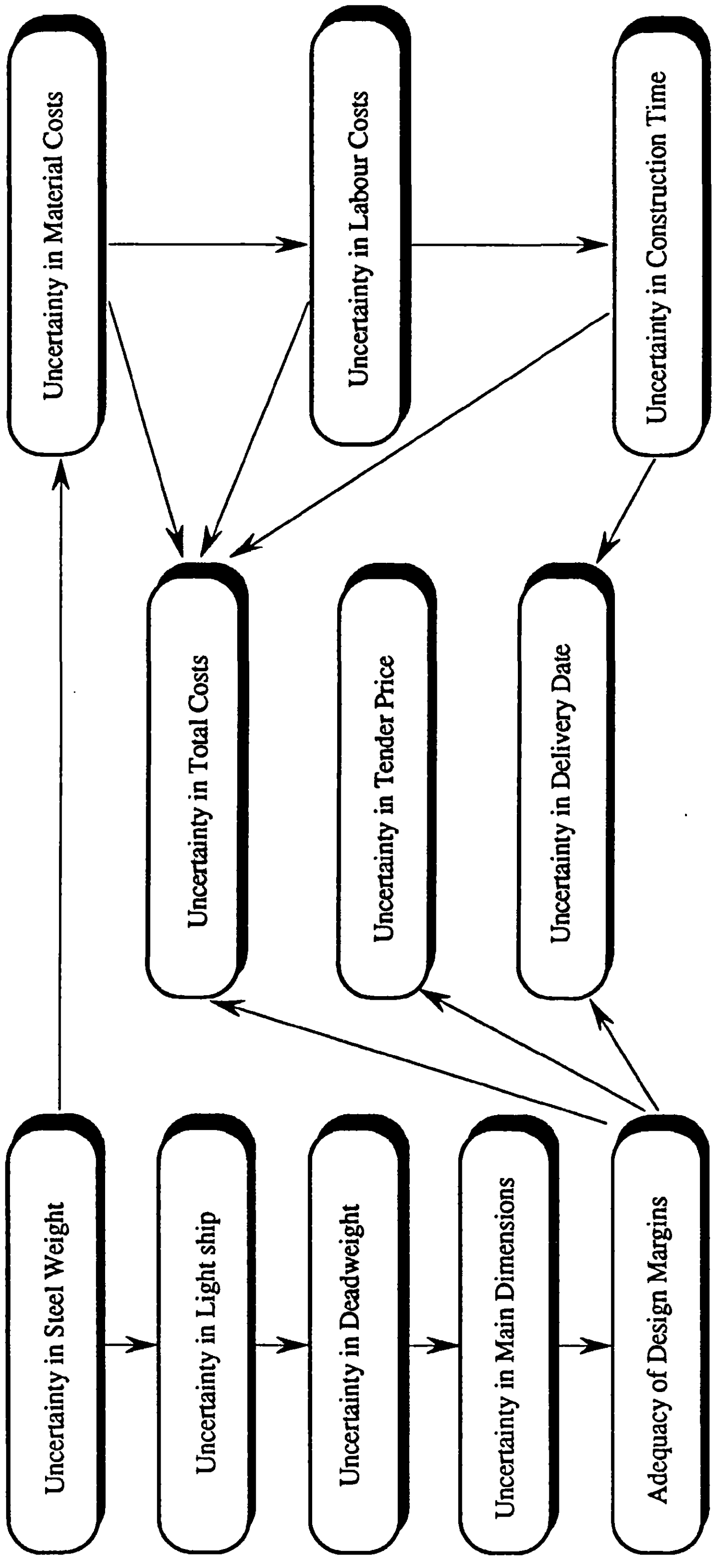


Fig. 15.1 Uncertainty in Preliminary Ship Design

b. the identification of solutions, and

c. the evaluation of solutions.

Objectives or goals should be quite specific with little room for variance. Nevertheless, in practice this is seldom the case since even a clear statement for the required function may be lacking in a specification of acceptable performance within the function. Typically where performance specifications are given, they are in terms of ranges of acceptable values, constraints on values, and expressions of preference. For example, in the offshore supply vessel design, the payload objective stated as :

"to carry a maximum deadmass of 2000 tonnes . . ."

may actually mean:

"if the maximum deadmass is less than 2000 tonnes, the designer will be penalised financially; if it is greater it does not matter as long as other requirement are met, and the price does not increase."

Identification of feasible solutions presents the most demanding part of the ship design process, and consequently is the most difficult to formalise. However, there are ideas which are totally original and past practice which provides some basis for locating possible solutions. In terms of numerical design, some of the overall concepts are well established such as the type of vessel, with a preferred geometry, and ability to operate in particular conditions. Thus, the designer is concerned with representing the possible ranges of solutions within the concept where such ranges come from decisions already made and facts already known. For example, if designing an offshore supply vessel for a role similar to existing vessel, this context could lead to an early conclusion that the length of such vessel is likely to be between 55 to 65 metres. An additional requirement about the type of cargo to be carried and the deck machinery to be installed might further narrow the range. These ranges represent the uncertainties in the solution space in numerical terms, and seem to depend on aspects of the design already fixed. As goals are elaborated, the ranges may be reduced to allow a focusing in on a satisfactory solution.

Whatever solution that is to be proposed needs to be evaluated to make sure whether it does indeed perform according to the requirements. Such evaluation involves the model of the solution, a model of its external environment and a model of the performance of the solution. Each of these involve assumptions and simplifications which will create uncertainty in the results. The sources of uncertainty are many and their interactions as mention earlier are complex. For example, in preliminary ship design, the power estimation may be carried out at different levels of detail. When such estimation is further used to determine the lightmass, further approximations are made and the uncertainty in power is carried along through to the new result. Much of the art of design is that of identifying the characteristics of most significance to be included in the model, and retaining some measure of the extent of the uncertainty involved in using the model.

15.2 REVIEW ON THE METHODS OF INCORPORATING UNCERTAINTY IN SHIP DESIGN

The nature of the problem, the type of uncertainty involved and the quality of the available design information often dictates the choice of technique. In general, the more accurate the technique the more information it requires and produces. As in all design matters, the choice of an appropriate method is a matter of balancing the need for accuracy and the time and data available in view of the use that will be made of the results. In the past, various methods of uncertainty have been taken into account in preliminary ship design. A few of the more important techniques are reviewed which include :

a. sensitivity analysis
b. use of simple probability theory
c. simulation
d. goal programming
e. Taylor series approach.

15.2.1 Sensitivity Analysis

This is perhaps the simplest method of taking account of uncertainty in the preliminary ship design. Sensitivity analysis involves making incremental changes to some main items which are usually known to have major influence on the measure of merits of the vessel or items which cannot be estimated accurately at the preliminary design stage because of their inherent variability over the life of the vessel. As an example, one can study the variation of ship main dimensions and block coefficient with changes in fuel costs using required freight rate as a criterion. This method may be used to :

a. discover the extent to which variables can be change without creating an unacceptable outcome; to determine the break-even point,

b. identify the important assumptions and determine how much they can be changed before an unacceptable result is produced,

c. investigate how much variables and assumptions may be changed before a chosen alternative becomes inferior to another alternative, and

d. systematically explore the solution space in order to clearly see the interrelationship between variables, constraints and outcome.

A sensitivity analysis provides much insight into where to concentrate further design work and how to reduce the effects of errors in assumptions. However, when large numbers of designs are involved, the results of the sensitivity analysis are usually to isolate designs which are relatively insensitive to variations in the operating parameter values. This method will be used to analyse the uncertainty for offshore supply vessel design.

15.2.2 Simple Probability Theory

Hutchison [15] describes a few ways of taking explicit account of uncertainty in ship mass and cost estimations. The mean and variance of the constituent masses, their centre of gravity and costs are used to obtain the mean and variance of the composite parts so that the confidence limits for different margins are known. As an example, for a simple summation :

$$y = \sum_{i=1}^{n} x_i \qquad \text{Eqn. 15.1}$$

$$E(y) = \sum_{i=1}^{n} E(x_i) \qquad \text{Eqn. 15.2}$$

$$Var(y) = \sum_{i=1}^{n} Var(x_i) \qquad \text{Eqn. 15.3}$$

where x_i could be the individual costs or masses.

Similarly, other expressions for product and quotients are given, so that the mean and variance of centres of gravity can be easily computed. In his paper, *Hutchison* assumed normal distributions and although some skewness can be present in the data for individual items of mass and cost as was shown, the resulting distribution is near normal when dealing with a reasonably large number of items together. For many design situations, this degree of detail could be considered sufficient and involves quite simple calculations.

A typical approach to mass in the preliminary design stage is to estimate the mass based on historical mass data plotted against some suitable basis, for instant cubic number. What is achieved by conventional methods is an estimate of the mean or expected trends in mass. If regression analysis is utilised and confidence bands are computed, measures of uncertainty can be obtained suitable even for such early design activities.

Given n pairs of data, $(x_1, y_1), \ldots (x_n, y_n)$, the least squares estimates of a_0 and a_1 can be easily obtained. These estimates can be expected to vary somewhat from sample to sample. However, it can be shown that both estimates are unbiased and hence that $\hat{a}_0 + \hat{a}_1 x$ is an unbiased estimate of $a_0 + a_1 x$. In addition, it can be shown that

$$\text{variance}(\hat{a}_0) = \frac{\sigma^2_{y|x}}{n}\left[1 + \frac{n\bar{x}^2}{\sum(x_i - \bar{x})^2}\right] \qquad \text{Eqn. 15.4}$$

and

$$\text{variance}(\hat{a}_1) = \frac{\sigma^2_{y|x}}{\sum(x_i - \bar{x})^2} \qquad \text{Eqn. 15.5}$$

and that both $\hat{a}_0$ and $\hat{a}_1$ are normally distributed, as each is linear combination of the values of y which are themselves normally distributed. Thus in order to obtain confidence intervals for $a_0 + a_1 x$ an estimate of the residual variance $\sigma^2_{y|x}$ must be obtained first. The sum of squared deviations of the data from the estimated regression line is given by $\sum(y_i - \hat{a}_0 - \hat{a}_1 x_i)^2$. This quantity is often called residual sum of squares. It can be showed that an unbiased estimate $\sigma^2_{y|x}$ can be obtained by dividing this residual sum of squares by n - 2

$$s^2_{y|x} = \frac{\sum (y_i - \hat{a}_0 - \hat{a}_1 x_i)^2}{n-2} \qquad \text{Eqn. 15.6}$$

The denominator, n - 2, shows that two degrees of freedom have been lost. This is because the two quantities $\hat{a}_0$ and $\hat{a}_1$ were estimated from the data, so there are two linear restrictions on the values of $y_i - \hat{a}_0 - \hat{a}_1 x_i$. A more convenient form for computation is given by

$$s^2_{y|x} = \frac{\sum y_i^2 - \hat{a}_0 \sum y_i - \hat{a}_1 \sum x_i y_i}{n-2} \qquad \text{Eqn. 15.7}$$

Thus it can be shown that the (100 - α) per cent confidence interval for $\hat{a}_0 + \hat{a}_1 x_0$ is given by

$$\hat{a}_0 + \hat{a}_1 x_0 \pm t_{0.5\alpha, n-2}\, s_{y|x} \sqrt{\left[\frac{1}{n} + \frac{(x_0 - \bar{x})^2}{\sum (x_i - \bar{x})^2}\right]} \qquad \text{Eqn. 15.8}$$

As an example, the above procedure is used for plot of lightship mass of the offshore supply vessel and its cubic number as shown in Fig. 15.2. If the designer proceeds on the assumption that his design might turn out with the lightship mass anywhere between the upper and lower 50 percent confidence bands, then he will have reasonably covered his design risks for the preliminary design stage.

15.2.3 Simulation

This is perhaps the most direct manner of dealing with uncertainty due to the conceptual simplicity of the analysis. Since it make used of random numbers, this technique is often quoted as Monte Carlo Simulation. Such technique was first proposed by *Hess* and *Quigley* [10] in 1963 and made popular by *Hertz* [11], [12] in 1964 and 1968 who also coined the word risk analysis in his classical paper [11] in the *Harvard Bussiness Review*. A complete description of the technique can be found in references [9], [10], [11], [12] and [13]. Use of this technique in ship investment problems has

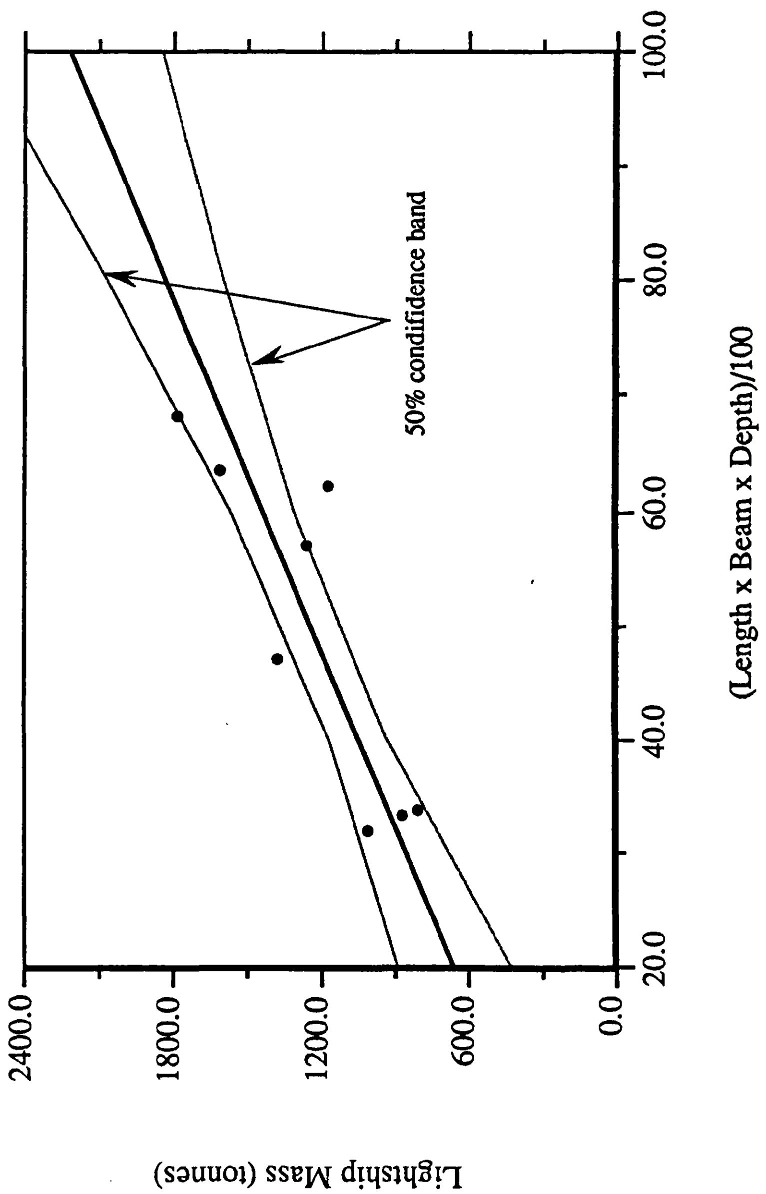


Fig. 15.2 Application of Confidence Bands for Lightship Mass Estimation

been limited so far but application in other industries can be found extensively particularly in oil recovery projects and chemical industry [16], [17] and [18]. One of the earliest papers advocating this technique was by *Klausner* [8] for shipbuilding investments followed by *Wolfram* [2] who proposed an analytic approach.

The Monte Carlo simulation technique is outlined in Fig. 15.3 and the major step includes:

a. *Defining the Variables* : This initial step is the obvious starting point of any quantitative analysis, that is, to define the measure of merit 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 in later section on how to deal with them.

b. *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 parameters for which there is some uncertainty about their values.

15.2.4.1 Defining Distributions for the Unknown , Random Variables

This is the stage where the professional expertise and judgement of a designer is involved. The final distribution of the measure of merit will generally depend on the distribution of the variables, that is, if all the variables are independent and are represented by a normal distribution, then it is known from the central limit theorem [2] that the distribution of the measure of merit 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.

b. The distribution can be assessed either objectively based on experimental data, nature of the variable or past historical record, or subjectively.

c. If opinions vary as to the nature, range, or shape of the distribution, then

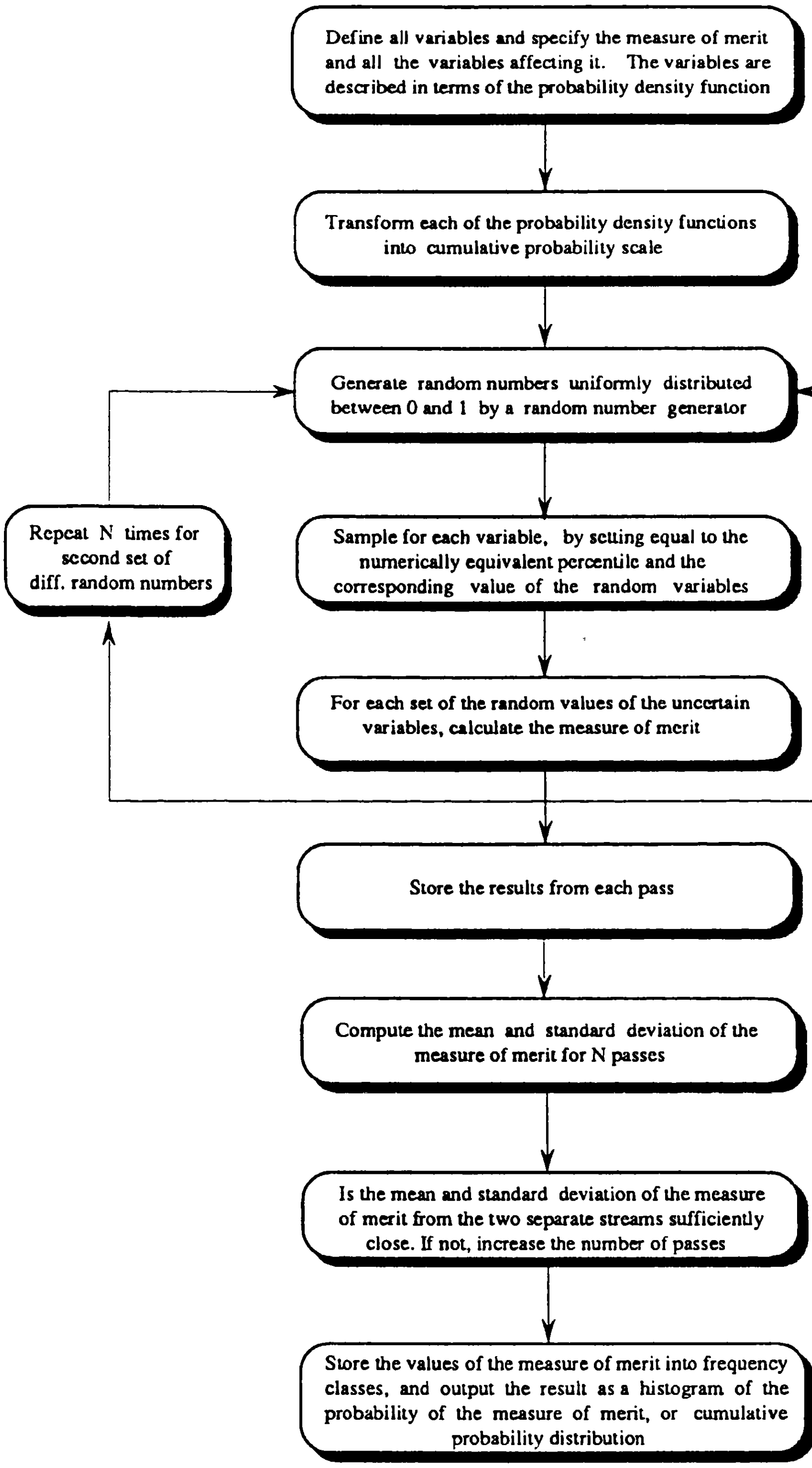


Fig. 15.3 Monte Carlo Simulation Technique

Table 15.1 Different Types of Distribution

No.	Type of Distribution
1	A variable can be described in the simulation by a single estimate provided by the user.
2	A variable can be described in the simulation by a PERT estimate of its mean which will be based on optimistic, pessimistic and best estimates provided by user.
3	A variable can 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.
4	A variable can 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.

various possible combinations can be tried for each complete run of the Monte Carlo analysis. However, four types of distribution are considered to be adequate to describe most of the variables and they are listed in Table 15.1 [22].

15.2.4.2 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 15 years and for salvage value is zero. If the ship's life is change to 12 years, will the salvage value change, and if the answer is yes, then the two variables are dependent. On the other hand if the estimate of salvage value remains unaffected then they are considered independent.

Dependencies cause problems in risk simulation because, when they are present, it is a mistake to sample independently from the probability distribution of the different variables. Theoretically, the simulation should first be sampled 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 a measure of merit. However, it cannot be used to indicate the effect of the dependence on the mean of the measure of merit or any other characteristic of the distribution of the measure of merit. One useful way of analysing dependencies is to calculate the distribution of the measure of merit assuming no dependencies, and the distribution of the measure of merit assuming total dependencies. A brief review of other more sophisticated ways to deal with dependencies is given by Hull [14].

15.2.4 Goal Programming

There are several variants on the method of goal programming, but the essential argument is that in cases where several objectives cannot be optimised simultaneously, a compromise objective should be optimised. The compromise consists of a linearly weighted function of the departures from some agreed level of each objectives. These 'agreed levels' are said to be goals.

In formulating the goal programming model, two extra concepts are introduced. A desirable level or goal for each objective must be determined. It is possible to determine the optimum value of each objective function alone and treat these as the goals. This is done in awareness that all the goals will not be achieved, and that the departures when they occur will be on the negative side, that is reality will fall short of the goal. Alternatively, the goals could be determined by the requirements of the decision maker. He may be satisfied with a level of output below the maximum, a utilisation of facilities below 100 percent and even a profit level below that is targeted. Having decided on the appropriate levels or goals, he then finds a strategy which will match the goals as close as possible.

The second new concept is that of weighting in the departures from the objective functions. This first of all allows priorities to be given to the various goals, and these priorities effectively turn the problem into a single objective linear programming problem. Alternatively, they can be thought as assigning a priority sequence to the objectives. The highest priority goal is satisfied first, and thence in order until no further goals can be achieved. Each goal, therefore, has full priority over lower-order priority. In the event that all goals are fully achieved, the designer should think once more about the levels chosen for the goals, since he may not have been sufficiently ambitious and better goals are in fact obtainable. The further drawback to this approach is that since each goal is only considered when its turn in the sequence arrives, the actual levels of those lower-priority objectives, whose goals are not met, may be a very long way from the set goals.

Usually the consequences of departures from the goals will depend on the sign (+ or -) of the departure. Exceeding the profit goal by £1000 is certainly of more benefit than a shortfall of the same amount. Again this can be allowed for in weights assigned to the departures. Weights should also take in account the units used to measure the goals, since objectives are likely to be expressed in term of money, hours or masses. One way of overcoming this could be to express departures as proportions by the relative importance of the objectives. In general mathematic terms, there are k objectives

$$Z_j = a_{j1}X_1 + a_{j2}X_2 + \ldots + a_{jm}X_m, \qquad j = 1, 2, \ldots, k \qquad \text{Eqn. 15.9}$$

to be maximised, subject to the m linear constraints

$$b_{1i}X_1 + b_{2i}X_2 + \ldots + b_{mi}X_m \le C_i, \qquad i = 1, 2, \ldots, n \qquad \text{Eqn. 15.10}$$

Suppose that goals $G_1, G_2, \ldots, G_k$ have been set for the k objectives. The departure of the objective Z_j from goal G_j can be expressed as

$$a_{j1}X_1 + a_{j2}X_2 + \ldots + a_{jm}X_m + d_j^- - d_j^+ = G_j \qquad \text{Eqn. 15.11}$$

The actual departure is $d_j^- - d_j^+$, where both of these terms are non-negative, but at least one is zero. Individually, the terms are interpreted as the amount by which the goal is exceeded (d_j^+) and the amount of the shortfall (d_j^-). Equation 15.11 now augment inequalities Eqn. 15.10 as constraints on the decision variables $X_1, X_2, \ldots, X_m$ which themselves have been augmented by the variables $d_1^+, d_1^-, d_2^+ \ldots, d_k^-$. The objective function to be minimised is a linearly weighted function of these departure variables, that is

$$w_1^+d_1^+ + w_1^-d_1^- + w_2^+d_2^+ + \ldots + w_k^-d_k^- \qquad \text{Eqn. 15.12}$$

Thus, in this general form, the problem has been formulated as a linear programming problem. With all of the weights non-negative, there is no possibility of an optimum with both d_j^+ and d_j^- positive. On the other hand, it may be tempting to encourage a departure in one direction, but not in the other. For example, if the goal refers to profit, most shipbuilding firms would welcome a value in excess of the set goal. This could be engineered by making w_j^+ negative. The method will adjust automatically provided that w_j^+ is less in absolute value than w_j^-, so that the benefit from a unit excess is less than the loss from a unit shortfall.

The above method has been successfully implemented in preliminary ship design studies. For further details, see for example references [19], [20] and [21].

15.2.5 Taylor Series Approach

The Taylor series approach has been successfully applied to incorporate uncertainty in the preliminary ship design by *Wolfram* [2]. He argued that this approach is better than the Monte Carlo simulation 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.

In any engineering economy problem, the object is to find the value of one quantity (perhaps RFR, IRR, or NPV) which is a function of many others, initial ship cost, and/or crew costs. This may be expressed in the following manner,

$$z = f(x_1, x_2, x_3, \ldots\ldots x_n) \qquad \text{Eqn. 15.13}$$

When the quantities $x_1 - x_n$ are not single values , as is often assumed, but each capable of a range of values, then z may be expanded as a Taylor Series,

$$z = f(x_1, x_2, x_3, \ldots\ldots x_n) = f(\mu_1, \mu_2, \mu_3, \ldots\ldots \mu_n) + \sum_{i=1}^{n}\left(\frac{\partial z}{\partial x_i}\right)_{\mu}(x_1 - \mu_i)$$

$$+\frac{1}{2}\sum_{i=1}^{n}\left(\frac{\partial^2 z}{\partial x_i^2}\right)_{\mu}(x_1 - \mu_i)^2 + \text{higher order neglected forms} \qquad \text{Eqn. 15.14}$$

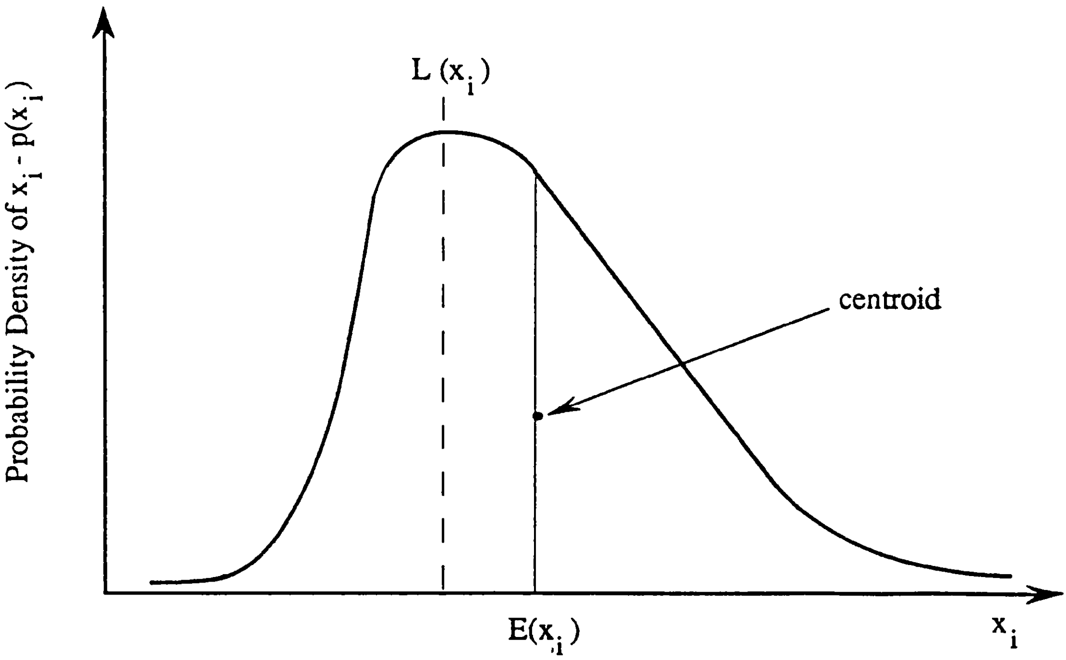


Fig. 15.4 Definition of Mean or Expected Value and Maximum Likelihood Value

The series as written above assumes that the variables $x_1 - x_n$ are independent and uncorrelated. The term $\mu_1 - \mu_n$ represent the mean or expected values of $x_1 - x_n$ and this is illustrated in Fig. 15.4. Also shown in Fig. 15.4 is the most likely value of x_i, or the 'maximum likelihood value' as it is known.

$$E(z) \approx E[f(\mu_1, \mu_2, \ldots, \mu_n)] + \frac{1}{2}\sum_{i=1}^{n}\left(\frac{\partial^2 z}{\partial x_i^2}\right)_{\mu} \sigma_i^2 \qquad \text{Eqn. 15.15}$$

Generally, in engineering economics, the second term is either zero or negligibly small and the mean or expected value of z is obtained by performing the usual deterministic calculations with the mean values of each of the parameters. Thus, the variance of the distribution of z is given by

$$\sigma_z^2 \approx \sum_{i=1}^{n}\left(\frac{\partial z}{\partial x_i}\right)_{\mu}^{2} \sigma_i^2 \qquad \text{Eqn. 15.16}$$

In a similar manner, the coefficient of skewness of z can also be obtained as a function of the skewness of the individual distributions of x_i and is given by

$$Sz = \frac{\mu_{3z}}{\sigma_z^3} = \frac{\sum_{i=1}^{n} \left(\frac{\partial z}{\partial x_i} \right)_{\mu}^{3} \mu_{3i}}{\left(\sum_{i=1}^{n} \left(\frac{\partial z}{\partial x_i} \right)_{\mu}^{2} \sigma_i^2 \right)^{3/2}} \qquad \text{Eqn. 15.17}$$

This method is obviously useful mainly when dealing with a relationship between several independent variables, and a dependent one. For example

$$\text{steel labour cost} = \text{steel mass x} \frac{\text{manhours}}{\text{tonne of steel}} \text{ x } \frac{\text{cost}}{\text{manhour}}$$

where every term in the right-hand side of the equation can have its own distribution.

15.3 APPLICATION OF UNCERTAINTY IN OFFSHORE SUPPLY VESSEL DESIGN

This section deals with incorporating uncertainties in the preliminary design of offshore supply vessels. Three methods will be considered in this study which include:

a. sensitivity analysis
b. application of certainty theory
c. application of Bayes' rule

15.3.1 Sensitivity Analysis of Offshore Supply Vessels

A sensitivity analysis is carried out to determine the order of merit of some parameters of offshore supply vessels which are of influence on internal rate of return (IRR). Seven parameters are improved by 10% from their original values, and the extension of ship's life from 15 to 20 years, one at a time. The basic ship data are given in Table 15.2. The vessel is predicted to be chartered with a day rate of £6200 for 330 days a year.

The analysis are carried out for two cases. Case A assumes no relative escalation of either internal rate of return or operating cost items. Case B assumes a relative escalation of crew costs 2.5% per annum. Crew costs are chosen to escalate relative to others since it is the cost item which is likely to increase faster in the future. The analysis is done with the view that the shipowner will charter the vessel. Thus items such as fuel costs, port charges, cargo handling charges and endurance will not be considered in this study. The computer program described throughout the thesis is kept the same for carrying out the sensitivity analysis except where some transformations being done in order to vary appropriate parameters within specific ranges.

Tables 15.3 and 15.4 give the results of 10% improvement in the different parameters for Case A and Case B. These parameters are discussed separately below and resulted changes in percentage of other features is also given.

Table 15.2 Basic Ship Data for Sensitivity Analysis

Parameter	Value
Length Overall	64.5 m
Breadth	15.5 m
Depth	6.5 m
Block Coefficient	0.73
Speed	13.5 knots

15.3.1.1 Capital Cost

Like any other vessel, capital cost is an important parameter for the offshore supply vessels and its reduction depends less on the shipowner than the competitive situation between shipyards and levels of wage rates in the country of construction. Therefore, the shipowner is always tempted to go to the shipyard with the least contract price and an acceptable delivery date..

A reduction of 10% in capital cost reduces hull and machinery insurance by 10% since such cost items are estimated from it. Tables 15.3 and 15.4 show that the internal rate of return is sensitive to the capital cost.

15.3.1.2 Steel Mass

For offshore supply vessels, steel mass forms a high proportion of the lightship. For the range of vessels considered, the steel mass to lightship mass ratio is found to be between 65 and 76%. Thus, any reduction of steel weight has an appreciable repercussion on other ship features including capital cost.

For the vessel under study, a reduction of 10% in steel mass, for constant displacement, increases the deadmass by 4.2% due to the reduction in lightship mass of 5.68%. Capital cost is decreased by 1.65% bringing hull and machinery insurance costs down by the same percentage. As a result, the internal rate of return is found to be very sensitive to the steel mass especially for Case B as shown in Table 15.4.

15.3.1.3 Installed Power

A 10% reduction in installed power calculated by the program brings the lightship mass down by 1.9% due to resulted reduction in machinery mass of 8.96%. As a consequence, the capital cost is decreased by 4.16%.

However, reduction in installed power is not easy to achieve due to possible deterioration in hull condition with passage of time causing the opposite effect of increasing this power to maintain a schedule speed. Thus, a shipowner would not be very concerned in reducing this parameter in search for more profit. Moreover, for offshore supply vessels, any reduction of power may reduce the day rate of such a vessel as charterers are very concerned with powering especially for anchor handling/tug/supply vessels and may favour a higher powered vessel if available at the same day rate.

15.3.1.4 Labour Wage Rates

A 10% reduction in shipbuilding wage rates brings the labour costs down by the same percentage and thus, decreases the capital cost by 5.25% which in turn reduces the hull and machinery insurance by the same amount.

Wage rates are unlikely to be reduced as they are dictated by the general economic environment and supported by national labour unions. They are, on the contrary, more likely to increase over the years. The shipowner, however, has the freedom to choose a country of construction with lower levels of wage rates.

15.3.1.5 Crew Costs

A reduction of crew costs, which may exceed 50% of the daily running costs, depends on the constraints upon shipowners to choose their crew. Shipowners flagging under flags of convenience have more flexibility to employ crew for lower wages than those under national flags employing nationals with higher wages.. Another alternative in reducing these costs is to automate the ship and then reduce crew number. This solution supposes that the shipowner is willing to invest in automation and to face traditional opposition from the national unions of seamen seeking to maintain high employment opportunities for their members. Apart from this, the shipowner has to comply with the regulation on the minimum number of crew allowed by Government authorities.

A 10% reduction in crew costs reduces operating costs by about 2.86%. For Case B where this cost item is escalated 5% annually, crew costs rank at a more important position compared to Case A where no escalation of such cost is being considered.

15.3.1.6 Steel Cost

The cost per tonne of steel is fixed by manufacturers depending on the market condition and world steel production. However, the overall steel cost can be reduced if the of steel ordered by shipyards is optimised by minimising scrap percentages.

A 10% reduction in the cost per tonne of steel decreases ship capital cost by 0.39% which in turn reduces the hull and machinery insurance by the same percentage. For the basis ship, steel cost is found to have little influence on the internal rate of return.

15.3.1.7 Time Off Hire

The 20 days per annum, assumed in the program to be spent for dry docking and repair, is decreased by 10% to measure the effect on the internal rate of return. This reduction increases the annual income by 2%. The period out of service is found to be quite influential towards internal rate of return as shown in Tables 15.3 and 15.4.

15.3.1.8 Ship's Life

The basic ship's life of 15 years is extended to 20 years. An increase of 5 years brings a fairly important increment in the internal rate of return. However, Goss [32] indicated that the conditions for the life extension may reduce this apparent advantage.

15.3.2 Application of Certainty Theory

This theory was developed for use in expert systems as with an attempt to overcome the problems associated with probability theory. In this theory, a 'certainty measure' is associated with every 'factual statement. Details of certainty theory have already been given in Chapter 11.

As an example of using the certainty theory , the problem of selecting a main machinery/propulsion system for an offshore supply vessel has been chosen. Significant simplifications have been adopted in the rules in order to illustrate the approach and assess its potential. The rules are written in the expert system shell 'Leonardo'.

Basically, the application tries to determine the most suitable main machinery/propulsion combinations from the following :

Table 15.3 Relative Importance of 10% Improvement in Different Features of Ship Performance (Case A : No Relative Escalation)

Ship's Features	Initial Value	Final Value	IRR (%)	% from Basic IRR
Basic Ship			11.21	
Capital Cost (x 10^3£)	9054.6	8149.2	14.60	30.24
Steel Weight (t)	975.0	887.5	11.72	4.55
Installed Power (bhp)	5075.0	4567.5	12.68	13.11
Labour Wage (£/hr)	6.05	5.45	12.89	15.00
Crew Costs (x 10^3£)	316.8	285.1	11.88	5.98
Steel Cost (£/ton)	300.0	270.0	11.33	1.08
Time out of Service (d)	20.0	18.0	11.99	6.96
Ship's Life (years)	15	20	13.10	16.86

Table 15.4 Relative Importance of 10% Improvement in Different Features of Ship Performance (Case B : 2.5% Escalation of Crew Costs)

Ship's Features	Initial Value	Final Value	IRR (%)	% from Basic IRR
Basic Ship			11.21	
Capital Cost (x 10^3£)	9054.6	8149.2	12.20	8.83
Steel Weight (t)	975.0	887.5	10.10	9.90
Installed Power (bhp)	5075.0	4567.5	10.38	7.41
Labour Wage (£/hr)	6.05	5.45	10.51	6.25
Crew Costs (x 10^3£)	316.8	285.1	9.97	11.06
Steel Cost (£/ton)	300.0	270.0	9.02	19.54
Time out of Service (d)	20.0	18.0	9.84	12.22
Ship's Life (years)	15	20	10.48	6.51

a. two engines-two controllable pitch propellers units
b. four engines-two controllable pitch propellers units
c. four engines-two controllable pitch propellers units with power take-off
d. diesel electric-two controllable pitch propellers units

Decisions are based on the following information provided by a user of the system :

a. approximate shaft power

b. propeller revolutions

c. height limitations in engine room

d. importance of reserve power

e. importance of reserve propulsion system

f. degree of manoeuvrability

g. degree of positioning control

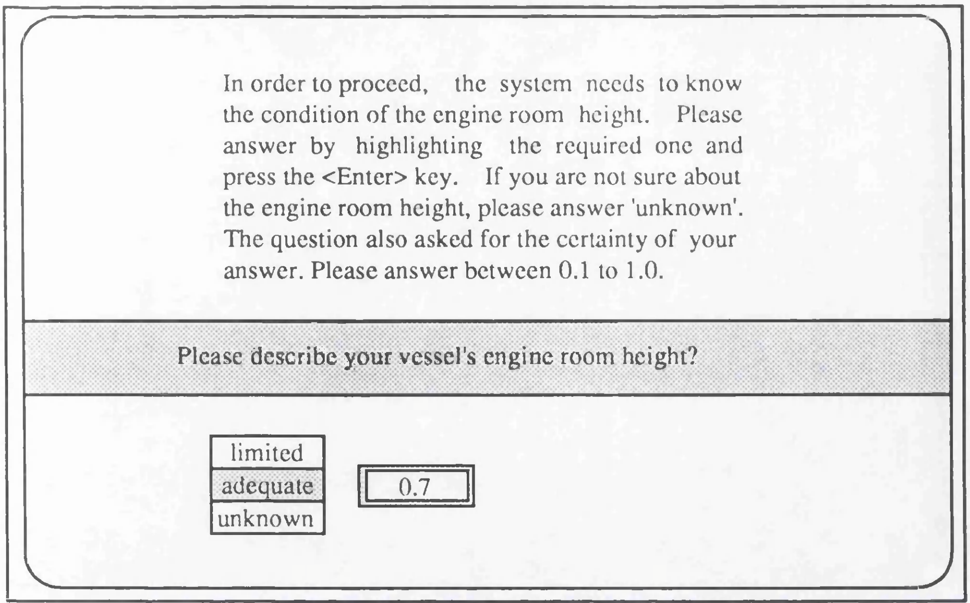
h. depth of water limitation

i. first cost limitation

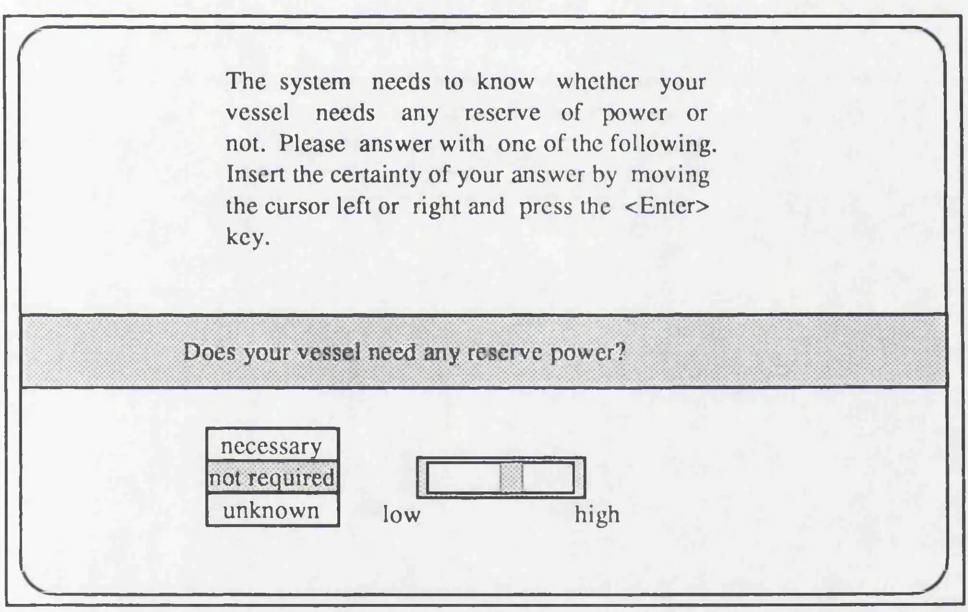
The system starts by asking the user the type of vessel that is to be considered either a pure supply vessel or an anchor handling/tug/supply vessel. Once the type of vessel is known, the user is then asked to enter the brake power and the revolution per minute of the propeller. The remaining questions regarding engine room height, reserve power and propulsion unit, degree of manoeuvrability, degree of positioning control, depth of water and first cost limitation will then be asked respectively. Each of these questions have to be answered with certain degree of certainty. The system will then select the best main machinery and propulsion arrangement based on the criteria input by the user. Figure 15.5 shows some of the rules used in developing the expert system for main machinery and propulsion system selection with certainty theory. Figure 15.6 shows some of the execution of the system during interfacing with the user while Fig. 15.7 and 15.8 show typical results for pure supply and anchor handling/tug/supply vessel.

```
/*      Selection of Main Propulsion System for Offshore Supply Vessels
/*      using Certainty Factor

/*      Initialise the type of uncertainty theory that is to be used.
/*      (Certainty Factor Method)

        control cf

        control threshold 0.01

/*      Select the type of vessel to be considered

        ask type_of_vessel

/*      Obtain the Brake Horsepower and Propeller Revolutions

        ask brake_power

        ask prop_revs

/*      Rules regarding the Engine Room Height

        if er_height is limited
        then height_factor is low    {cf 1.0)

        if er_height is adequate
        then height_factor is high   {cf 1.0)

        if er_height is unknown
        then height_factor is low    {cf 0.7}

/*      Rules regarding requirement  for large amount of Reserve Power

        if reserve_power is necessary
        then power_factor is high   {cf 1.0}

        if reserve_power is not required
        then power_factor is low    {cf 1.0}

        if reserve_power is unknown
        and type_of_vessel is pure_supply
        then power_factor is low    {cf 0.7}

        if reserve_power is unknown
        and type_of_vessel is ah_tug_supply
        then power_factor is high   {cf 0.7}
```

Fig. 15.5 Example of Rules Associated with Certainty Theory



(a) On the Description of Engine Room Height



(b) On the Necessity of Redundant Power

Fig. 15.6 Examples of Interaction during Execution of System

Type of Vessel	:	Pure Supply
Brake Power (kW)	:	2000
RPM of Propellers	:	230

Describe your vessel engine room height	:	limited	{cf 0.80}
Does your vessel require reserve power?	:	not required	{cf 1.00}
Does your vessel require reserve propeller?	:	not required	{cf 1.00}
Does your vessel require manouevring and dynamic positioning capability?	:	optional	{cf 0.70}
Describe the water depth in ports of service	:	shallow	{cf 0.80}
Expenditure for engine first cost	:	limited	{cf 1.00}

Results :

Two engines - two controllable pitch propellers	{0.69}
Four engines - two controllable pitch propellers	{0.21}
Four engines - two controllable pitch propellers with power take-off	{0.10}
Diesel/Electric - two controllable pitch propellers	{0.03}

Fig. 15.7 Example of Execution for Pure Supply Vessel (Certainty Theory)

Type of Vessel	:	Anchor Handling/Tug/Supply
Brake Power (kW)	:	8000
RPM of Propellers	:	200

Describe your vessel engine room height	:	adequate	{cf 0.75}
Does your vessel require reserve power?	:	necessary	{cf 0.90}
Does your vessel require reserve propeller?	:	necessary	{cf 0.90}
Does your vessel require manouevring and dynamic positioning capability?	:	necessary	{cf 1.00}
Describe the water depth in ports of service	:	shallow	{cf 0.80}
Expenditure for engine first cost	:	limited	{cf 1.00}

Results :

Four engines - two controllable pitch propellers with power take-off	{0.75}
Four engines - two controllable pitch propellers	{0.22}
Two engines - two controllable pitch propellers	{0.11}
Diesel/Electric - two controllable pitch propellers	{0.03}

Fig. 15.8 Example of Execution for AH/Tug/ Supply Vessel (Certainty Theory)

15.3.3 Application of Bayes' Rule

Bayes' rule is one component of probability theory which provides a way of computing the probability of a hypothesis being true given some evidence related to that hypothesis. The degree of relationship between evidence and hypothesis is described by three numbers: logical sufficiency (LS), logical necessity (LN) and a-priori probability of the hypothesis (PP). PP is the probability of the hypothesis being true prior to observing evidence. If the evidence is observed to be true, PP is increased by the LS factor. Conversely, if the evidence is found to be false, PP is decreased by the LN factor. The values of LN and LS in an expert system need to be adjusted according to the degree of uncertainty. Details of this rule has already been discussed in Chapter 12.

In this study, the application of Bayes' rule is used to select the main engine and propulsion unit for the offshore supply vessel discussed previously. Figure 15.9 shows some of the rules used to develop the system while Fig. 15.10 and Fig. 15.11 show examples of the executions.

15.4 CONCLUSION

This section provides a summary of some of the methods used to take uncertainty into account in preliminary ship design calculations. Two methods, certainty theory and Bayes' rule, have been introduced to incorporate uncertainty in the preliminary selection of main engine and propulsion system.

Certainty theory provides a means of manipulating subjective estimates of certainty such that the calculated certainty values are intuitively attractive:

a. The resulting certainty values always lie between 0.1 and 1.0 and the meaning of the values are all well defined.

b. If two contradictory rules are applied, such that the certainty of one is equal to the certainty of the other, then their effects cancel out.

The Bayesian approach to probability relies on the concept that one should incorporate the prior probability of an event into the interpretation of a situation. However, applying Bayes' rule using a strictly probabilistic point of view is difficult for a number of reasons :

```
/*      Selection of Main Propulsion System for Offshore Supply Vessels
/*      using Bayes' Rule
/*      Initialise the type of uncertainty theory that is to be used.
/*      (Bayes' Rule Method)

        control bayes

/*      Select the type of vessel to be considered

        ask type_of_vessel

/*      Obtain the Brake Horsepower and Propeller Revolutions

        if type_of_vessel is pure_supply
        or type_of_vessel is ah_tug_supply
        and brake_power is known
        and prop_revs is known
        then input_data is obtained

/*      Rules regarding the Engine Room Height

        if input_data is obtained
        and er_height is limited                {ls 2.0 ln 0.2}
        then engine is  '2 engine 2 cp'         {prior 0.6}

        if input_data is obtained
        and er_height is adequate               {ls 2.0 ln 0.2}
        then engine is  '4 engine 2 cp'         {prior 0.6}

/*      Rules regarding requirement  for large amount of Reserve Power

        if reserve_power is necessary           {ls 2.0 ln 0.2}
        then engine is '4 engine 2 cp'          {prior 0.6}

        if reserve_power is not required        {ls 2.0 ln 0.2}
        then engine is '2 engine 2 cp'          {prior 0.6}

/*      Rules regarding  requirement for Dynamic Positioning

        if dynamic_postioning is necessary      {ls 2.0 ln 0.2}
        then engine is '4 engine 2 cp -PTO'     {prior 0.6};
             engine is '4 engine 2 cp'          {prior 0.3}

        if dynamic_postioning is optional       {ls 2.0 ln 0.2}
        then engine is '2 engine 2 cp'          {prior 0.6};
             engine is '4 engine 2 cp'          {prior 0.6}
```

Fig. 15.9 Example of Rules Associated with Bayes' Rule

Type of Vessel	:	Pure Supply
Brake Power (kW)	:	2000
RPM of Propellers	:	230

Describe your vessel engine room height	:	limited
Does your vessel require reserve power?	:	not required
Does your vessel require reserve propeller?	:	not required
Does your vessel require manouevring and dynamic positioning capability?	:	optional
Describe the water depth in ports of service	:	shallow
Expenditure for engine first cost	:	limited

Results :

Two engines - two controllable pitch propellers	{0.86}
Four engines - two controllable pitch propellers	{0.32}
Four engines - two controllable pitch propellers with power take-off	{0.17}
Diesel/Electric - two controllable pitch propellers	{0.08}

Fig. 15.10 Example of Execution for Pure Supply Vessel (Bayes' Rule)

Type of Vessel	:	Anchor Handling/Tug/Supply
Brake Power (kW)	:	8000
RPM of Propellers	:	200

Describe your vessel engine room height	:	adequate
Does your vessel require reserve power?	:	necessary
Does your vessel require reserve propeller?	:	necessary
Does your vessel require manouevring and dynamic positioning capability?	:	necessary
Describe the water depth in ports of service	:	shallow
Expenditure for engine first cost	:	unlimited

Results :

Diesel/Electric - two controllable pitch propellers	{0.68}
Four engines - two controllable pitch propellers with power take-off	{0.56}
Four engines - two controllable pitch propellers	{0.33}
Two engines - two controllable pitch propellers	{0.07}

Fig. 15.11 Example of Execution for AH/Tug/ Supply Vessel (Bayes' Rule)

a. The application of Bayes' rule requires the availability of all relevant prior and conditional probabilities. Obtaining this information can be very difficult in practice.

b. Bayes' rule is mathematically correct only if all possible outcomes are not connected. Although one may reformulate concepts, this often results in a model that does not correspond to the intuitive concepts of the expert.

c. As the knowledge-base size grows, it becomes virtually impossible to change one probability without causing ripple effects that incorrectly change other probabilities required to retain mathematical assumptions such as $P(H_1) + P(H_2) + \ldots + P(H_n) = 1$.

Nevertheless, conclusions from using an expert system shell for uncertainty studies are that structuring a problem is relatively easy, and does not involve any conventional programming knowledge. Interaction is also simple and the simplicity to deal with uncertainties and make explanations is valuable.

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CHAPTER 16

DISCUSSION, CONCLUSION AND FUTURE DEVELOPMENT

CHAPTER 16

DISCUSSION, CONCLUSION AND FUTURE DEVELOPMENT

16.0 DISCUSSION ON OFFSHORE SUPPLY VESSEL DESIGNS

Offshore supply vessels have a comparatively short history of about 40 years but within that period they have evolved, as must all types of vessel, to follow the changes taking place in their trade. The most noticeable changes being size and speed but perhaps the most significant being manoeuvring and control characteristics. The early designs for the Gulf of Mexico evolved the long working deck aft of the forecastle and accommodation block but were of modest size and speed with machinery uptakes abreast the working deck. They were not expected to be at sea in bad weather as travelling distances were small.

The advent of the North Sea meant that bad weather was endemic and must be considered in the design. Economies of scale became increasingly attractive as crew numbers are almost constant. Changes in variety and types of drilling fluid and bulk solids required many more distinct tanks and hoppers. Increasing mass densities of mud put emphasis on cargo deadmass but access to hopper tanks and large angle stability considerations meant that the designs are not true deadmass carriers. Such vessels have design~~s~~ drafts less than their maximum geometrical draft and thus greater than maximum freeboard to satisfy internal space needs and large angle stability requirements.

As conditions change from one oilfield to another, vessels rendered less suitable are sold to work in more appropriate fields or sold for other duties such as standby vessels. This style is likely to continue.

As in much of engineering, control and positioning systems have grown in importance and in accuracy with many detailed but significant improvements. The ship master today is able to pin point his location and maintain station without being secured to the seabed or to a platform.

New designs will continue to show increased size and power and demand for smaller and cheaper vessels will be met by buying previous generations of new designs after they have been some years in service. The large world fleet may thus defer new buildings of modest size and limit new vessels to always be larger and faster.

16.1 POSSIBLE DEVELOPMENT OF OFFSHORE SUPPLY VESSELS

Forecasts of the future are frequently wrong but they are constantly made to try to establish owners' requirements for future new vessels which may expect to work in their designed oil field for at least ten years and have a total working life of perhaps 25 years.

16.1.1 Size

Scale economies and the increased deck load of newer platforms and floaters will continue to encourage the provision of larger supply vessels with probably a trend to further increase in length/ beam ratios, perhaps a length of over 80 metres and a length/beam ratio beyond 4.5. *Froude* numbers may be relatively static but the absolute speed will respond to increase of length. Depth will be defined by large angle stability and draft by deadmass and port limits. However, ports which are unable to keep pace with increase of size may be overtaken by those who can.

16.1.2 Hull Form

Distinction is needed between anchor handling/tug/ supply vessel forms and pure supply vessels. The hull form for an AH/T/S must provide excellent water supply to the propellers and thus has a fine aft body with a modest block coefficient. The hull form for a pure supply vessel needs to generate displacement with a relatively high block coefficient and accept that at full speed it is inefficient in propulsion terms. However, this is an outward voyage situation and even then full power may not be needed being reserved for emergency and looking good on the prospectus for chartering, provided it does not increase the charter rate. Wave impact at the fore end is important and needs strength to survive it together with breakwaters.

16.1.3 Powering and Fuel Efficiency

Initially, the present arrangement of twin screw, twin engine will ccntinued to be used. Incentives for fuel savings will also make the newer fuel-efficient engines more attractive. Higher horsepower will be installed in some vessels, enabling them to have some towing/anchor-handling capability, though generally with a decrease in efficiency in the straight supply mode.

Engine installations in the larger vessels will require about 5000 to 7000 shaft horsepower. Some form of diesel-electric installation becomes worthy of consideration for the big vessels, especially if multi-role mission requirements are specified and economic incentives forthcoming. A substantial fire fighting capability combined with multiple thrusters would be an excellent candidate for the diesel-electric concept.

Fuel efficiency is another factor that will become increasingly important. Fuel efficient engines, improved hull forms, and careful selection of propellers are a few of the many items where improvements can be made. Energy management system that consider the input of distance, time available, sea state, and sequence of discharge are being considered and need to be encouraged as they give the best route, speed and revolutions for the voyage.

16.1.4 Manoeuvring Ability

Stern thrusters are a requirement on the very large offshore supply vessels. Skeg-mounted transverse tunnel thrusters will be normal, and high-lift high-angle rudders, possibly independently controlled, will be fitted on some vessels. However, the installation of azimuthing Z-drive main propulsion units would eliminate the need for rudders and stern thrusters yet still provide superior handling qualities.

Joy stick controls are needed for proper utilisation of the manoeuvring devices. The control interface components of the system would be compatible with a dynamic positioning system that will ultimately be required on many of the vessels.

16.2 DISCUSSION ON THE APPLICATION OF EXPERT SYSTEMS IN OFFSHORE SUPPLY VESSEL DESIGN

Though the application of computers in preliminary ship design has evolved since the early 1960's, none of the programs developed have been universally adopted nor kept in use over a long period of time. This may be due the fact that preliminary ship design requires many empirical relationships which can reflect the attitudes of the designers, the amount of data available and the ship types being considered. The cost of updating the programs may have reduced the usefulness of the programs over a relatively long time with great changes in ship types and databases.

It was not difficult to create the logic of the computer programs to carry out preliminary ship design studies. Most of the effort involved matching the various subprograms to give reasonable results within an acceptable range of vessel type, 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 offshore supply vessels.

Some of the factors which reduce the acceptability of preliminary ship design programs are the large number of empirical relationships used to estimate the design parameters. These empirical relationships need to be improved especially for mass, centre of gravity and cost estimation.

This thesis describes a computer model for the preliminary design and operation of offshore supply vessels utilising expert system programming. The various programs written are shown in Table 16.1. One significant advantage of using an expert system is that the program is easily updated as most of the empirical relationships are kept in individual frames which can be changed or edited once and be effective whenever they exist in the program. Moreover only the edited frame needs to be recompiled instead of the whole program and this reduces the compilation time.

The economic study incorporated into the program, which should always be a fully integrated part of ship design, serves as a basis for comparison between alternative solutions and as a basis to measure any consequence of technical variable changes such as alteration in particular variables or operation by owner or charterer.

Table 16.1 A Complete Overview of the Computer Program Developed

Model	Name	Description	Computer Time (secs)
I	OSVDP	An interactive program for the design of offshore supply vessels using iterative methods to evaluate the main parameters, hull forms development, stability, group mass, freeboard, powering, propulsion, seakeeping and manoeuvring, shipbuilding and operating costs, and economic analysis.	1200
II	OPTOSVD	An interactive optimisation program for determining the main parameters of the offshore supply vessels. Two non-linear constraint optimisation methods are incorporated in the program, that is, Hooke and Jeeves; and Nelder and Mead.	420
III	MOSVOP	A computer program to model the offshore supply vessels operation in transporting the required materials to an offshore rig.	420
IV	MOSVCF	A program for the selection of the main engine and propulsion units for offshore supply vessels incorporating Certainty Theory.	120
V	MOSVBR	A program for the selection of the main engine and propulsion units for offshore supply vessels incorporating Bayes' Rule	120

* The computational time is based on the program working on an IBM PC 286 XT.

An interactive optimisation program (OPTOSVD) is also developed to evaluate the potential of having the mathematical optimisation procedure in the expert system. Unlike previously written optimisation programs, the OPTOSVD allows the user to view the progress of the optimising procedure. Two distinguish nonlinear constraint optimisation methods, *Hooke* and *Jeeves*, and *Nelder* and *Mead* are incorporated in the program. The program also allows the user to change from one optimisation method to another without much difficulty.

Preliminary ship design consists largely of producing a number of design alternatives so that one or more of the designs can be chosen for further consideration. However, designs have to operate in environments and markets that can only be guessed and with a number of uncertainties. For years, designers have tried to incorporated uncertainties in an explicit manner in the preliminary design phase. Though numerous methods have been experimented with, the incorporation of uncertainties still remains unpopular. The main reason for such setbacks is that in conventional programming, to include uncertainties into the preliminary ship design program is very complex. With the existence of expert systems, uncertainties in the preliminary ship design can be incorporated more readily. An expert system allows the fuzziness of knowledge to be insert without much difficulty. Various theories have been developed to accommodate such fuzziness in expert systems. Two of the most popular theories include Certainty Theory and Bayes' Rule.

The application of the Certainty Theory and Bayes' Rule have been demonstrated by developing a program for the selection of main engine and propulsion systems for the offshore supply vessels. The program guides the user to select the best system for his vessel based on confidence levels in answering some of the appropriate questions. Though this program is limited to the selection of main engine and propulsion system, it shows the easiness and potential of incorporating uncertainties in ship design programs.

16.3 CONCLUSION OF STUDIES

As has been observed, each chapter in this thesis has been provided with a brief conclusion. However, this section gives the overall conclusion on the research.

a. Most of the empirical equations originally developed to estimate the main dimensions and group masses by past researchers for offshore supply vessels are no longer suitable to be used for modern vessels. The empirical equations developed in this thesis are considered valid since the database consists of vessels built since 1980.

b. Pure supply vessels have relatively higher block coefficient than anchor handling/tug/supply vessels. In the latter type, a good supply of water to the propeller is essential resulting in a relatively low value of midship area coefficient and longitudinal prismatic coefficient. The increased carriage of high mass density drilling fluids such as oil based mud means that deadmass is increasing in importance for pure supply vessels and is reflected by the higher values of block coefficient

c. The initial stability of offshore supply vessels is higher than conventional vessels of the same length in order to satisfy the internal space needed and the large angle stability requirements. Thus, most of these vessels are operating at design draughts less than their maximum geometrical draughts.

d. The initial sketch technique used in the development of hull forms for the offshore supply vessel produced results with acceptable accuracy for the preliminary design stage. This approach eliminates the need for hand sketch on the drawing board, the digitising stage and initial fairing routine. With this method a more defined hull form of the offshore supply vessel and its design characteristics has been made available at the early design stage.

e. The MARIN method was found to be suitable in estimating the effective power of offshore supply vessels. For pure supply vessels with a target speed, the propeller and machinery can be optimised although consideration is also given to efficient running at lower speeds. As for anchor handling/tug/supply vessels, the propeller and machinery may be optimised for towing at a modest speed or indeed for bollard pull and the resulting possibly excessive free running speed at full power accepted provided efficient running at lesser power is possible.

f. A seakeeping program based on two dimensional strip theory has been developed. The seakeeping qualities of the offshore supply vessel can be described in term of box scores. The box scores are composed making use of information from the seakeeping criteria and the wave height distribution of the North Atlantic. Information that can be drawn from the box scores is the percentage of time the vessel could be expected to operate in her environment without violating the specified criteria. The seakeeping characteristics of a moderate size offshore supply vessel operating in the North Atlantic has an index of 0.76 for a complete year.

g. In the preliminary design stage, the manoeuvring characteristics of the offshore supply vessels can be regarded as linear and the empirical equations developed by past researchers can be used to estimate the manoeuvring characteristics of such vessels. A computer program has been developed to evaluate the course stability, minimum rudder area and the turning predictions of such vessels.

h. The required freight rate or the internal rate of return is suitable to be used as a measure of merit for offshore supply vessels. Based on the parametric studies given in Chapter 14, for vessels range between 800 to 3600 tonnes and having block coefficient of 0.75, the plots of required freight rates shows the economies of greater size and the general disadvantage of greater speed which within the range considered is never counterbalanced by carrying more cargo. For such vessels, the effect of fuel cost and number of crew on the required freight rates are negligible.

i. A computer program on the operational modelling of offshore supply vessels has been developed. The model consist of technical, operational and economic analysis of the supply characteristics. Like any other service vessels, a simple model to study the the operational characteristics of offshore supply vessel is very useful. Such a model would help either the owner or operator to plan the pattern of supplying materials which not only reduces operating costs but also reduces downtime of the offshore rig. From a case study done in Chapter 9, it shows that the as the distance between the rig from supply base increase, the vessel utilisation and rig downtime increases. Increasing the vessel deadmass would decrease the vessel sailing time, utilisation and rig downtime, but would increase the daily operating costs..

j. Vessels may be built with extra power even though the maximum power may never be utilised. This will make the vessel more attractive to charterer even though the required freight rate may be slightly heigher. As mentioned in Chapter 14, a vessel having a design speed of 16 knots but operating at 14 knots would only increased the required freight rate by 1.6 £/tonne.

k. The preliminary design procedure should be subdivided into various stages, which allow the identification of the important variables and their influence on the required freight rate. 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 required freight rate in the previous stage of the design.

16.4 FUTURE DEVELOPMENT

Expert systems are practical. Programs are commercially available which can be tailored to match the needs and solve the problems associated with preliminary ship design. The cautions are that expert systems cannot do everything and that care is needed in applying expert systems to ensure the success of the projects. Knowledge acquisition takes a significant amount of work. The time of human experts is required to install the knowledge into the system.

The computer model developed for selection of the main engine and propulsion system with certainty theory could be expanded and applied to marine power plant design in several steps :

a. to search for the candidate machines constituting the plant,

b. to determine the acceptable numbers and sizes of machines,

c. to select the optimal combination of machinery considering the initial and operational cost in varied life cycle situations, and

d. to display the design result including an approximate layout of the plant.

The remaining features of the ship can then be generated from the layout of the plant together with cargo needed to be carried. Though, this method may need a lot of database in terms of engine specifications, however with systematic arrangement of input such specifications would reduce the computational time.

Since the expert system package (*Leonardo*) used can be connected to a statistics package, a simple probability method as suggested by [15] in Chapter 15, could be incorporated to obtain confidence limits in evaluating the masses of the vessel. This method could be extended even to confidence limits for costings.

The maintenance effort to update a program even without major changes is an obstacle to the useful life of a design program which is usually specific to a particular class of vessel and rarely in continuous use. However with the application of expert systems, such effort of updating is reduced. As knowledge is gained, simple empirical relationships can be readily replaced by more scientific ones and the user is better able to check the relationships and their limits in the program. Ignorance of the limits of accuracy of the many empirical relationships when a program is used by newcomers to it can be dangerous.

Interactive computing takes much computing time as well as much user time but it may remain essential for design programs. Without the human expert who is constantly being updated from the technical press and market influence, the program cannot be properly guided in its decision taking. Graphical output is also an essential supplement to numerical output to show trends and is normally part of an expert system package.

Finally, it is hope that this thesis will render a significant contribution in the development of offshore supply vessels and expert system application in their preliminary design.

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APPENDICES

APPENDIX A

PRELIMINARY DEVELOPMENT OF HULL FORM BY INITIAL SKETCH TECHNIQUE

1.0 INTRODUCTION

A

Ship's hull form may be developed by several sketches which are later transformed into a scaled drawing where offset data can be generated. This procedure is repeated several times to achieve the most suitable solution. Such laborious procedure requires a large amount of time and effort. The availability of more powerful mini and micro computers supported by better graphic display has encouraged computer aided hull design which has developed considerably since 1970. Perhaps not enough attention has been given to creating hull forms of reasonable accuracy for use in the early stages of design decision making.

The shape of a hull surface of a ship is a result of the designer's interpretation of a form to meet the design requirements. This interpretation is subjective in nature and is normally based on knowledge and experience with some amount of imagination. In practice, with the same principal dimensions, two designers can produce different hull forms while fulfilling the same design requirements. This nature of 'design freedom' still remains even in the era of advanced computer technology. Thus, the initial rough sketches play an important role in the ship design process regardless of whatever methods and technology are being applied.

One of the essential requirements of computer aided hull form development is to define the ship surface in terms of mathematical expressions. However, due to the complexity of its shape, it is extremely difficult, if not impossible, to express the ship surface in terms of a single equation. This problem is overcome by dividing the ship into several regions or patches longitudinally and vertically according to the complexity of its shape. These patches are then brought together at the chosen boundary curves, for example, stern profile, parallel middle body boundary curves and stem profile. Transverse sections are also required at various stations including midship to complete the hull form. Apart from the principal dimensions, these boundary curves and sectional curves become the initial input data which may be derived either from standard series, parent design or from hand sketches. The desired design parameters are achieved either by adjusting these curves or by imposing the design parameters while creating them.

2.0 BASIC CRITERIA

The effectiveness of a computer approach used in developing hull form should be based on the following criteria :

a. *Interactiveness* - The approach should enable the designer to create, access and modify the design at various levels in an interactive manner. The proper utilisation of graphics presentation could improve the level of interactivity.

b. *Simple and Schematic Sketch Procedure* - The sketches should be created by a simple procedure which require a minimum of input data. It is also important to handle these sketches systematically in order to avoid irregular or wild shapes.

c. *Smoothness and Fairness* - Adequate quality of smoothness and fairness which is suitable for preliminary design purpose. Appropriate curve fitting and fairing methods should be used to ensure the above requirement.

d. *Adequate Output Information* - The output should provide adequate information for further design analysis and for presentation purpose.

e. *Quick Result* - To enable the designer to explore more alternative solutions so as to find the best possible hull form to fulfil the desired design requirements.

These are the basic criteria which, in the author's opinion, could justify the effectiveness of a computer approach for hull form development for preliminary design purpose. However, there are other criteria which should not be neglected such as user friendly, small memory, good graphics presentation and compatibility.

2.1 The Proposed Approach

The proposed computer approach for hull form development from simple sketches is based on basic philosophy and its criteria discussed previously. The general idea regarding this approach is illustrated diagrammatically in Fig.A.1.

Basically, the ship is divided into three regions, that is forward, parallel middle body and aft. These regions are connected by the boundary curves of the parallel

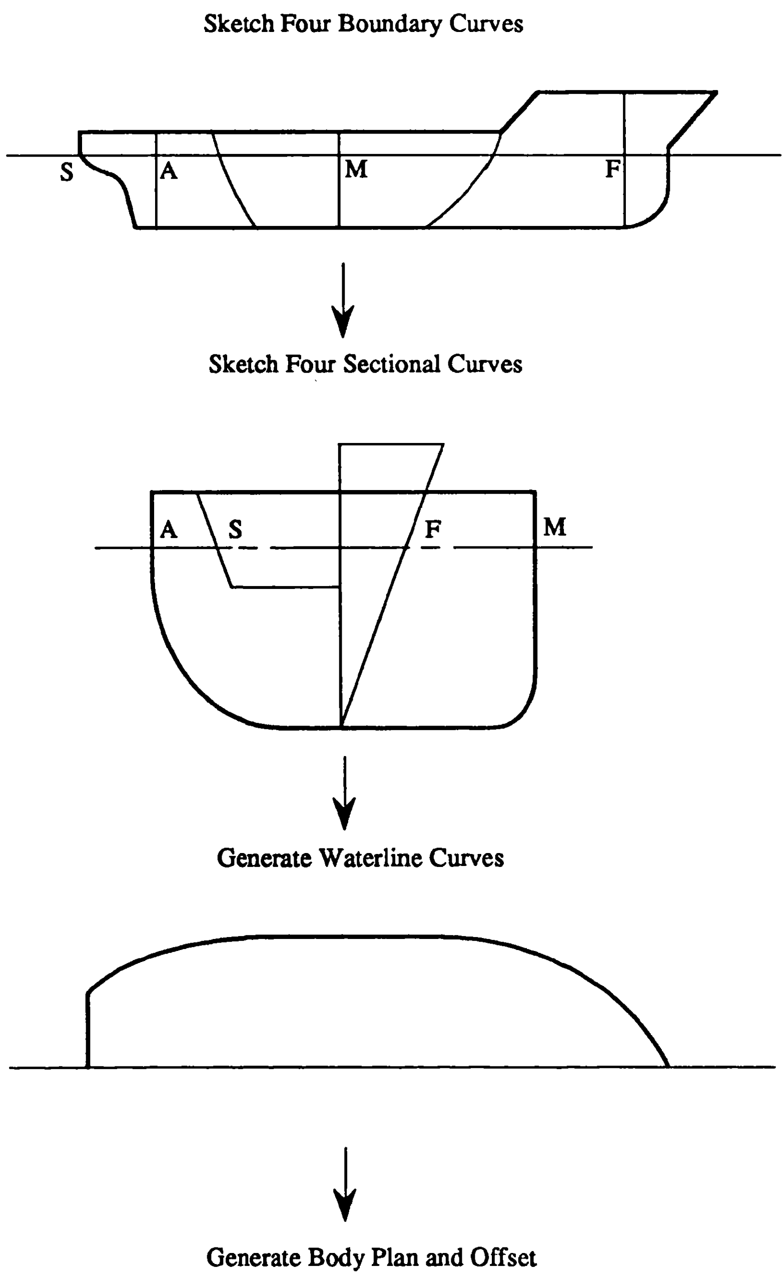

Fig. A.1 The Proposed Computer Approach for Hull Form Development middle body. The forward region ends with the stem profile and the after region ends with the stern profile. The profile of the after and forward sheer are considered to be part of the ship profile.

Three cross sectional curves are required to define the ship surface that is, at midships, and immediately before the stern, and where the stem profile begins. If the ship has a transom stern, then an additional sectional curve of the transom stern in a plane which is parallel to the inclination angle of the transom line should be included. The sketches of the profile curves and cross section curves are drawn or produced by the computer using minimum input data.

The combination of four boundary curves and three or four cross sectional curves will produce seven initial points for the waterline curves to be generated. By using a suitable curve generation technique, a smooth and fair curve which passes through all the seven points can be generated to produce the waterline curves.

After defining the appropriate end shapes of the waterline curves, either by free hand, or imposing suitable end conditions, the complete half breadth plan can be produced. Vertical interpolation will be made at every station to generate a complete body plan or offset data for further design analysis.

Since the proposed approach is specifically for the preliminary design stage, the emphasis is towards the creation of the sketches and how to organise these sketches in order to develop an approximate hull form. To organise the proposed computer approach, it is suggested that each design task is placed in a separate individual module, as shown in Fig. A.2. The important reason for such an arrangement is to enable a systematic programming structure to be written in order to avoid confusion and repetition which could lead to excessive memory and execution time.

3.0 SELECTION OF CURVE GENERATION TECHNIQUES

One of the most important factors which influence the effectiveness of the computer approach for hull definition is the type of curve or surface generation technique employed. Unlike most of the existing computer approaches which only rely on one method, this approach utilises all possible curve fitting methods available.

After a careful investigation and examination of several well known curve fitting techniques, which include Bezier curves, B-spline curves, cubic splines, parabolic curves, parabolic blending, polynomial with different orientations, and tangential arc, it was decided to use only some of these techniques to carry out the proposed task. The decision was based on the following characteristics :

a. *Requirement* - Either it is for generating a curve from a few points or to smooth the curve from a complete set of points.

b. *Smoothness and Fairness* - An adequate quality of smoothness and fairness for the preliminary design stage.

c. *Non mathematical* - Only the methods which require minimum understanding of mathematical formulation were chosen.

d. *Predictable Result* - To avoid the use of the methods which could produce unpredictable results.

With regard to the above mentioned points, the author decided to incorporate the following criteria for the computer approach for hull developments.

a. *Deck Curve* : B-spline, parabolic or straight line.

b. *Section Curve* : B-spline, tangential arc, polynomial and/or parabolic blending.

c. *Stern and stem profile* : B-spline and tangential arc.

d. *Middle Boundary Curve* : B-spline.

e. *Waterline Curve* : B-spline with special treatment or cubic spline.

Details of some of these techniques are included in Annex A.

4.0 COMPUTER APPROACH FOR SKETCHING SHIP HULL FORM

Since the first efforts to involve digital computers in ship design, almost every aspects of the design tasks has been extensively computerised. However, the involvement of computers in creating the sketch of initial ship hull form, especially at the preliminary design stage has been given limited attention.

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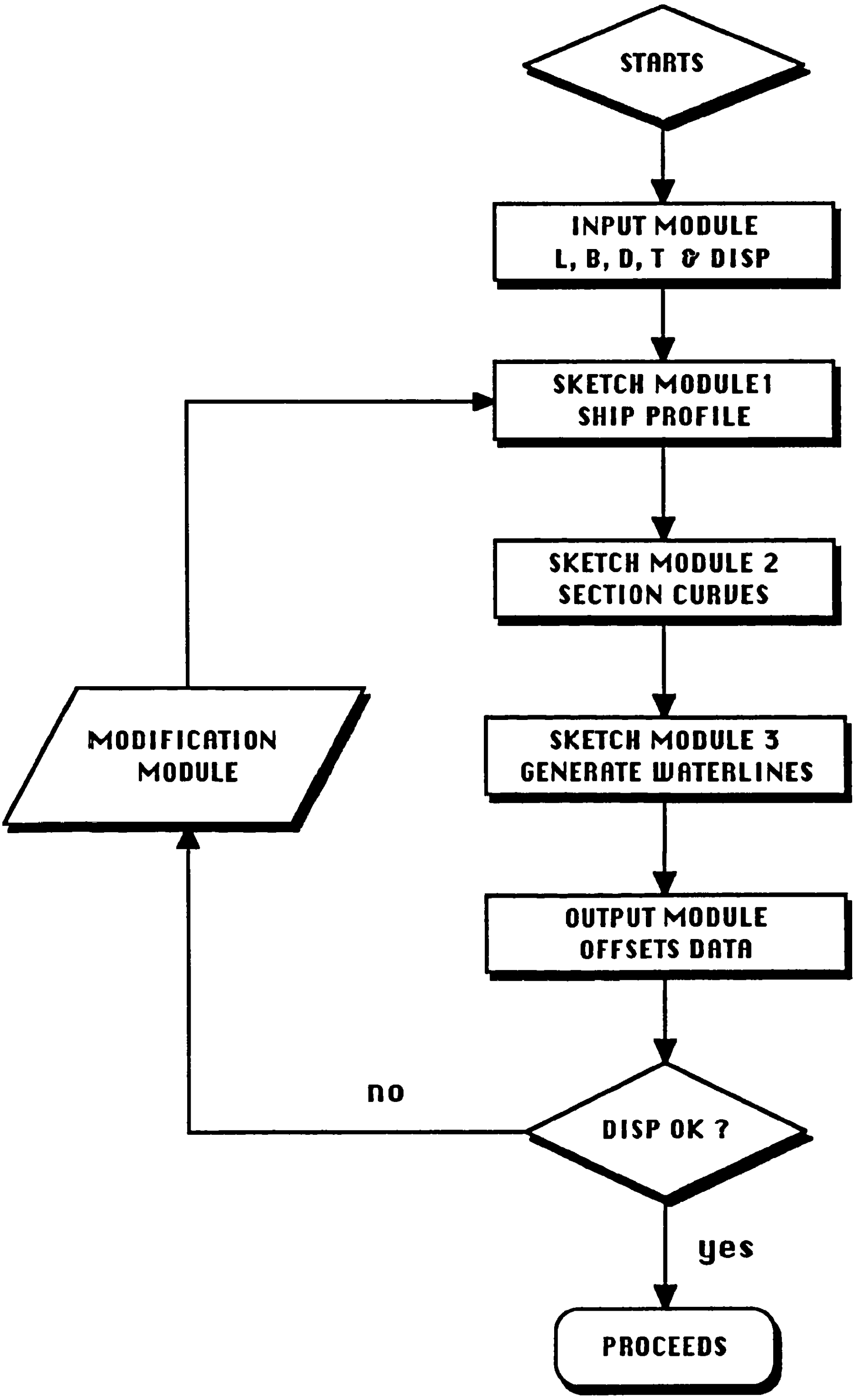

Fig. A.2 Arrangement of Modules

Today, despite the existence of powerful computer graphics with various facilities for sketching purposes, only a few of the design or drafting software provide some means of creating a sketch for initial hull form curves. In an attempt to promote a better utilisation of computer for the sketching process, an approach for a simple and systematic sketching procedure by computer is proposed in this study.

4.1 Advantages and Limitations of Computer Sketches

In contrast with the traditional hand sketch method, a computer sketch approach can offer several advantages which include :

a. eliminates the need for hand sketches and reduces the error due to the digitising process, hence improving the accuracy of the initial data.

b. by making a proper selection of curve fitting methods improves the smoothness and fairness of the initial sketches.

c. it allows the geometrical properties of the sketches to be calculated automatically, which in turn enables the designer to access and modify the sketches before going to further design tasks.

The limitations inherent in all the curve fitting methods restrict the freedom of the sketching process in which not all shapes can be sketched by computer as in a manual sketch and for some simple and obvious shapes, computer sketches may not be the most economical solution.

4.2 Important Characteristics

In order to implement a computer approach for sketching purposes which is suitable for creating ship curves and to ensure the effectiveness of the approach, the following characteristics have to be incorporated :

a. *Minimum Input Data* - Only limited and readily available data should be used, such as co-ordinates of control points, radius of arc, and slope.

b. *Continuous and Smooth Curve* - The sketch of the ship curves should be continuous and smooth although it may require a combination of several curve fitting methods.

c. *Wide Variety of Shapes* - For preliminary design it is essential to create various shapes of ship curves.

d. *Adequate Graphics* - For a good sketching process an adequate graphics presentation is essential in order to help the designer make a good decision.

4.3 Sketching Procedure

Most of the existing computer sketch approaches make use of a specific curve generation technique such as Bezier curve, or B-spline curve. Each of these techniques has a significant influence on the overall sketching procedures. Another important feature of the existing approaches is that, almost all the desired design parameters or geometrical properties such as area, slope, moment, centroid, have to be defined and entered before the curve can be generated. For the preliminary design stage, this approach is not suitable since most of the data are not available until the curves have been generated.

Unlike these approaches, the proposed approach presented in this study allows various suitable generation techniques to be used and the calculation of geometrical properties or design parameters will only be done after the curve has been generated. The desired design parameters can be achieved through adjusting the initial sketch.

5.0 METHODS OF EXTRACTING DATA FROM THE SKETCH

It is very important to consider a suitable method of extracting the data from the initial sketches before implementing the computer sketch approach. The main reason is, that the method used will define the type of data which is going to be utilised in the proceeding design task.

The data produced by the sketches is considered to be raw data and therefore not fully ready to be used for developing the hull form. The sketches of profile and boundary curves are presented in x - z co-ordinates, whereas the sketches of the sectional curve are presented in y - z co-ordinates, as shown in Fig. A.3. Before these data can be used to generate waterlines curve, they have to be interpolated vertically, Basically, there are two interpolation methods suitable for this study. These are, the polynomial least square method and the linear interpolation method. Care has to be taken in selecting either one of these methods depending on the nature of the curve and desired accuracy.

5.1 Polynomial Least Square Method

The curves produced by the sketches can be represented by a high order polynomial equation. The order of the curve can be selected according to the complexity of the curve. One of the main advantages is that once the appropriate equation has been found, then the exact x and y co-ordinates of any waterline can be interpolated. Figure A.4 illustrates the application of the polynomial interpolation method to calculate the exact x - z and y - z co-ordinates at the required waterline.

However, the polynomial interpolation method suffers from several difficulties. A polynomial curve may not pass through every data pair and using a higher order could create unwanted inflexions. For complex shapes, knuckles and flats require extra conditions before the curve can be interpolated successfully.

5.2 Linear Interpolation Method

This method is much simpler than the previous method and can be used to interpolate almost any shape provided the points along the curve are closely spaced. It is also easier to implement and requires less computational effort and memory capacity.

The only disadvantage is that, if the sketch data is thinly spread, then it could affect the accuracy of the interpolated points. To avoid this, more data is required especially at the portion where the slope of the curve changes very rapidly. Further details regarding this method can be found in Reference [4].

From the sketch shown in Fig. A.4, seven interpolated points of (x, y, z) co-ordinates for every waterline can be deduced. Table A.1 shows an example of the interpolated points for design waterline curves using the linear interpolation method.

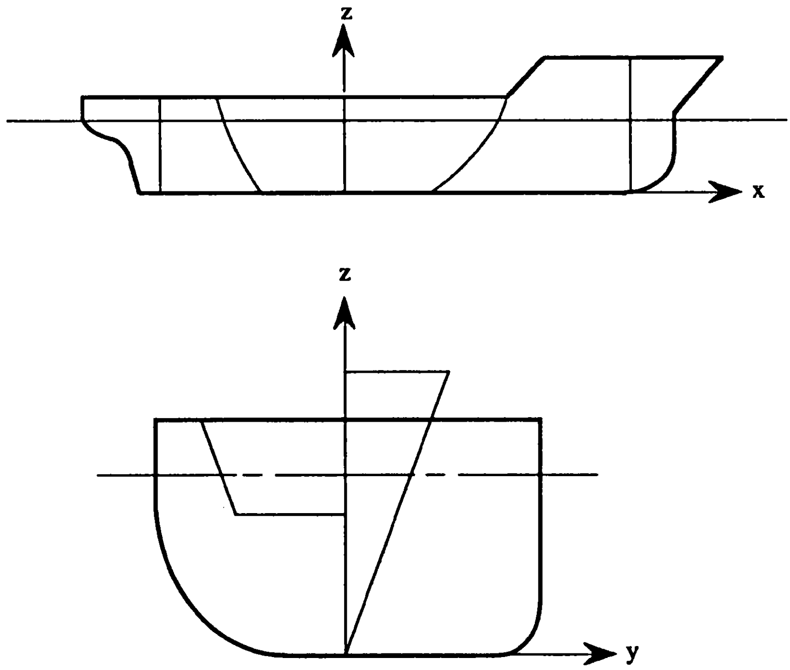

Fig. A.3 Sketch of Ship Profile and Sectional Curve

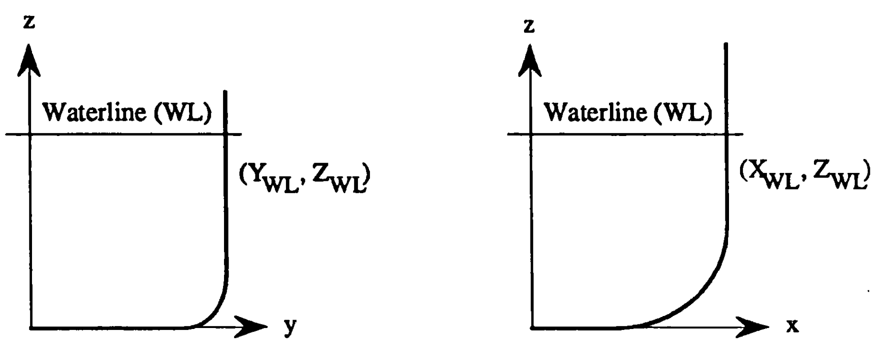

Fig. A.4 Polynomial Interpolation

6.0 METHOD OF GENERATING WATERLINE CURVES

Having done the interpolation procedure, the data is now ready to be used as control vertices for generating waterline curves. Figure A.5 shows an example of the basic polygon derived from these control vertices at the design waterline.

To generate a smooth and fair curve which passes through every control vertice, there are three possible methods which could be used, which are piece wise cubic spline, parabolic blending and B-spline curve with special treatment. Each of these methods has its own advantages and limitations to be considered before selecting it. These are given in Annex A.

7.0 BODY PLAN AND OFFSET DATA

After completion of the waterlines curves, the body plan curves and the offset data of the ship can be generated. This task requires an interpolation process in the x direction in order to extract y - z co-ordinates of all the waterlines at every station. Similar interpolation methods, which have already been discussed in the previous section, could be used for this purpose.

Using B-spline curve fitting techniques, or other suitable methods, the sectional body curves can be drawn smoothly from the interpolated data. However, the B-spline technique does not ensure that the curve should pass through all the interpolated points, especially at the lower appendages due to rapid change of its slope. To solve this problem, more intermediate waterlines are needed, especially at this portion. If this solution does not satisfy the designer, perhaps other methods, such as the parabolic blending technique, could be used with extra care in order to avoid unwanted inflexion. However, due to the large memory storage needed, the complete body plan will not be generated in this study.

The interpolated data produced at this stage is good enough to be used as an offset data for further design analysis, such as hydrostatics and stability calculations as well as for generating initial body lines at further design stage. The body plan in Fig. A.6 compares the offset data obtained from the computer program with an existing offshore supply vessel. The differences between the program output and the existing vessel are small; the accuracy is enough for the preliminary design stage.

Table A.1 Interpolated Points at Design Waterline

Station	X	Y	Z
1	25.10	0.00	4.105
2	23.40	2.15	4.105
3	12.50	5.91	4.105
4	0.00	5.91	4.105
5	13.00	5.91	4.105
6	19.60	3.45	4.105
7	26.00	2.30	4.105

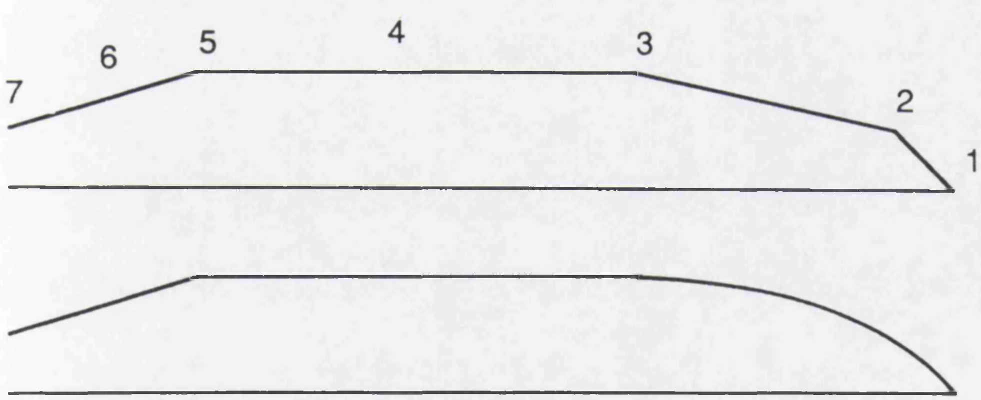

Fig. A.5 Basic Polygon and Waterline Curve

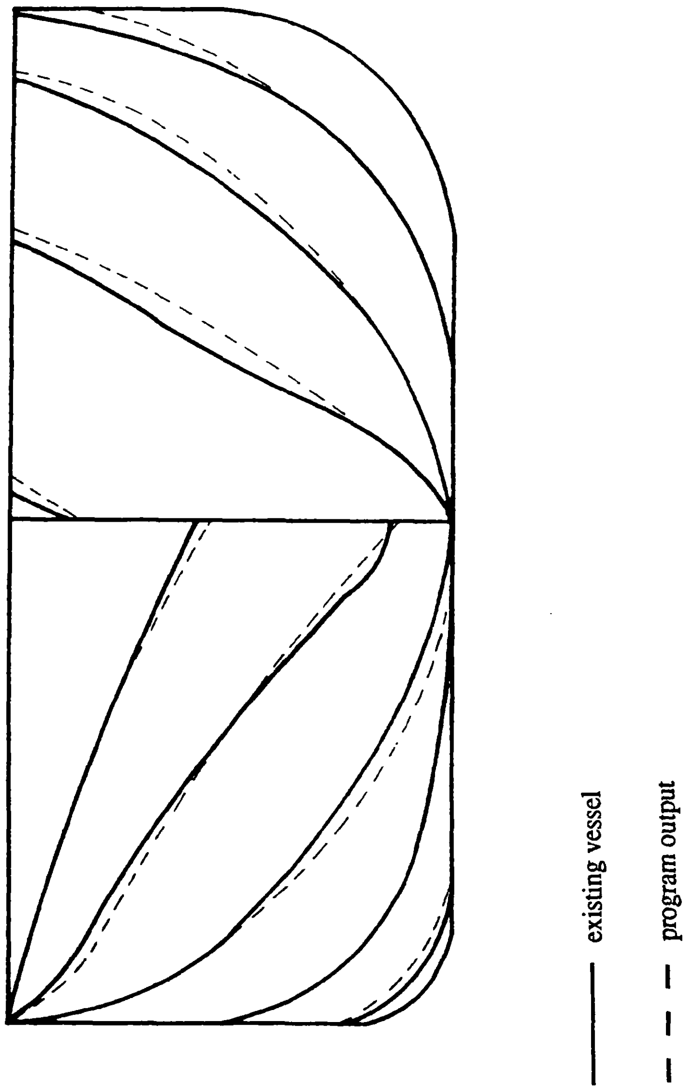

Fig. A.6 Comparison Between Program Output and Existing Vessel

8.0 CONCLUSION

In an attempt to improve the effectiveness of computer usage in the ship design field, a computer approach for hull definition specifically for the preliminary design stage has been proposed. Though in this study, emphasis is laid on the development of hull forms of offshore supply vessels, the same approach could be extended to develop any shape of hull form adequate for the preliminary design stage from relatively few and simple sketches.

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ANNEX A

CURVE GENERATION TECHNIQUES

A1.0 B-SPLINE CURVE

B-splines are a special class of polynomial with unique properties that result in several practical advantages compared to other spline function and polynomial. The theory of B-splines was first suggested by *Schnoenberg* [8].

A1.1 Mathematical Formulation

Let P(t) be the position vectors along the curve as a function of parameter t. The B-spline curve generation is given by

$$P(t) = \sum_{i=0}^{n} P(i).N_{i,j}(t) \qquad \text{Eqn. A.1}$$

where

$P(i)$ = the n + 1 defining polygon vertices

$N_{i,j}(t)$ = weighting function of the curve define by the recursion formula :-

$$N_{i,j}(t) = \begin{cases} 1 \text{ if } X_i \le t \le X_{i+1} \\ 0 \text{ if otherwise} \end{cases} \qquad \text{Eqn. A.2}$$

and

$$N_{i,j}(t) = \frac{(t - X_i).N_{i,j-1}(t)}{(X_{i+j-1} - X_i)} + \frac{(X_{i+j} - t).N_{i+1,j-1}}{(X_{i+j} - X_{i+1})} \qquad \text{Eqn. A.3}$$

X(i) are the elements of knot vector and parameter t varies from 0 to t_{max}. For computational purposes the limit of the index is as follows:

(a) j varies from 0 to k
(b) i varies from 0 to (number of polygon + k - j)
(c) t varies from 0 to t_{max}

(d) t_{max} equals (number of polygon - k + 2)
(e) order of curve

A1.2 Properties of Curves

The curve generated by B-splines has the following properties :-

(a) The curve passes through the first and last vertices and the slope at both ends is defined by the slope of the first and last polygon respectively.

(b) It has a non-global basis, thus local modification is allowed without affecting the entire curve.

(c) Flat, knuckle and discontinuities of curves can be generated by putting multiple vertices at the desired location.

(d) The order of the curve can be varied without being constrained by the number of vertices.

The combination of these properties has made B-splines technique a very practical tool for creating ship curves and, furthermore, it can be handled interactively.

A2.0 B-SPLINES WITH SPECIAL TREATMENT

The basis of this method is the B-splines curve generation technique. However, a B-splines curve does not necessarily pass through all the intermediate vertices. For this reason special treatment has to be made to the intermediate vertices. This method is specially used for generating the waterline curves whereby the curve should pass through all the seven vertices (refer to Section 6). To illustrate the application of this method an example is shown below.

Let A, B and C be the control vertices with the ordinates of (X_a,Y_a), (X_b,Y_b) and (X_c,Y_c) respectively.

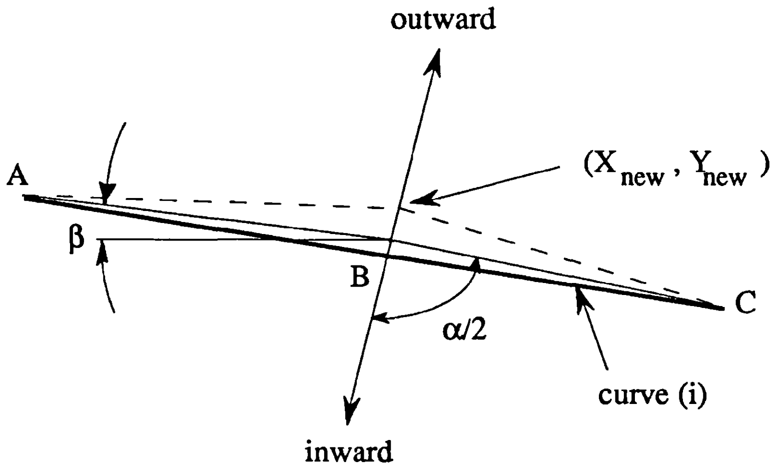

Fig. A.A Movement of Point B

Using the ordinary B-splines method, a curve (i) can be produced, as shown in the above diagram. However this curve does not pass through point B. By changing the ordinates of (X_a,Y_b) to (X_{new},Y_{new}), a new curve, which lies nearer to point B, will be generated. The process is then repeated several time until a curve which passes through point B has been found.

To maintain the fairness of the curve, it is suggested that the increment of vertices B should be in the direction of the arrow shown in the diagram (that is $\alpha/2$). Thus the new control vertices become :

$$X_{new} = X_b \pm t \times \cos(\alpha / 2 - \beta) \qquad \text{Eqn. A.4}$$

and

$$Y_{new} = Y_b \pm t \times \sin(\alpha / 2 - \beta) \qquad \text{Eqn. A.5}$$

where

α = angle of ABC

$\beta = \tan^{-1} [(Y_a - Y_{new})/(X_{new} - X_a)]$

\+ if the direction of increment is outward

\- if the direction of increment is inward

A3.0 CUBIC SPLINE

The concept behind the mathematical splines is similar to the physical lofting spline, which is widely used in the drawing office. In ship design, this spline is used to smooth and fair the curve from a given set of offsets. A piece wise cubic spline is mainly used for creating waterline curves and buttock lines.

A3.1 Mathematical Formulation

The equation for a single parametric cubic spline segment, in terms of a parameter t is given by

$$P(t) = \sum_{i=1}^{4} B_i t^{i-1} \quad ; \quad t_1 < t < t_2 \qquad \text{Eqn. A.6}$$

where

P(t) = the position vector of any points on the spline which is represented by [X(t), Y(t), Z(t)]

B(i) = the coefficient determined by specifying four boundary conditions for the spline segment.

The boundary conditions for each cubic spline segment consist of the two end points and the tangent vector at each end.

A3.2 Properties of Curve

The curve generated by the cubic spline technique has the following properties :

a. It passes through all the points provided that the condition $X_{i-1} < X_i < X_{i+1}$ is followed.

b. The curve is smooth although it may not necessarily be fair. It has second order continuity at the joints between each segment.

c. The end slope of the curve can either be free end or clamped according to the desired slope, with the exception of zero and infinity.

d. Cubic splines cannot generate flat surfaces and knuckle line, and multiple vertices are not allowed.

For these reasons, great care has to be taken in using this method for generating ship curves. Perhaps extra conditions may have to be imposed to generate a curve which has a straight portion, such as waterline curve.

A4.0 PARABOLIC BLENDING

The parabolic blending technique was first suggested by *Overhauser* [9]. This interpolation scheme considers four consecutive points simultaneously. A smooth curve between the two interior points is generated by blending two overlapping parabolic segments. It has a unique way of creating a curve which passes through all the given data, except the first and last points. It is normally used to generate body plan and waterline curves.

A4.1 Mathematical Formulation

For n number of points $(X_i, Y_i)_{i=1 \text{ to } n}$, a blending curve $C_i(t_i)$ is formed between an adjacent pair of points which is represented as follows :

$$C_i(t_i) = [1 - t / t_0] P(r)_i + t / t_0 \times Q(s)_i \qquad \text{Eqn. A.7}$$

where

t_0 = distance between the adjacent points

$$= \sqrt{(X_{i+2} - X_{i+1})^2 + (Y_{i+2} - Y_{i+1})^2}$$

t = internal division within each segment

$= t_0 \times J / \text{Ndiv}$ where Ndiv=Number of division and

$$P(r)_i = (X_i,Y_i) + r[(X_{i+2},Y_{i+2}) - (X_i,Y_i)]/d + \alpha r\left[(d-r)[(X_{i+1},Y_{i+1}) - (X_i,Y_i)] - U[(X_{i+2},Y_{i+2}) - (X_i,Y_i)]\right]$$

Eqn. A.8

$$Q(s)_i = (X_{i+1},Y_{i+1}) - (s/e)[(X_{i+3},Y_{i+3}) - (X_{i+1},Y_{i+1})] + \beta s(e-s)\left[[(X_{i+2},Y_{i+2}) - (X_{i+1},Y_{i+1})] - V[(X_{i+3},Y_{i+3}) - (X_{i+1},Y_{i+1})]\right]$$

Eqn. A.9

$$U = \frac{[(X_{i+1} - X_i)(X_{i+2} - X_i) + (Y_{i+1} - Y_i)(Y_{i+2} - Y_i)]}{\sqrt{(X_{i+2} - X_i)^2 + (Y_{i+2} - Y_i)^2}}$$ Eqn. A.10

$$V = \frac{[(X_{i+2} - X_{i+1})(X_{i+3} - X_{i+1}) + (Y_{i+2} - Y_{i+1})(Y_{i+3} - Y_{i+1})]}{\sqrt{(X_{i+3} - X_{i+1})^2 + (Y_{i+3} - Y_{i+1})^2}}$$ Eqn. A.11

$$d = \sqrt{(X_{i+2} - X_i)^2 + (Y_{i+2} - Y_i)^2}$$ Eqn. A.12

$$e = \sqrt{(X_{i+3} - X_{i+1})^2 + (Y_{i+3} - Y_{i+1})^2}$$ Eqn. A.13

$$\alpha = 1/\left[d^2U(1-U)\right] \qquad \beta = 1/\left[e^2V(1-V)\right]$$ Eqn. A.14 & 15

$$r = Ud + t\cos(\phi_1) \qquad s = t\cos(\phi_2)$$ Eqn. A.16 & 17

$$\cos(\phi_1) = [(X_{i+1} - X_i)(X_{i+2} - X_i) + (Y_{i+1} - Y_i)(Y_{i+2} - Y_i)]/(t_0 d)$$

Eqn. A.18

$$\cos(\phi_2) = [(X_{i+2} - X_{i+1})(X_{i+3} - X_{i+1}) + (Y_{i+2} - Y_{i+1})(Y_{i+3} - Y_{i+1})]/(t_0 e)$$

Eqn. A.19

A4.2 Properties of Curve

The curve generated by the parabolic blending technique has the following properties :

a. The curve starts from the second point, passes through all the intermediate points and ends at the second last point.

b. The curve is continuous and smooth in the first derivatives but is not necessarily fair. It often creates undesirable waviness if the points are not properly spaced out.

c. The flat side, knuckle and high curvature curve can be generated by making a series of closely spaced points at the desired location.

APPENDIX B

SOLUTION OF THE EQUATIONS FOR MOTION

1.0 GENERAL SOLUTIONS

The surge mode is assumed to be decoupled from the other modes. Moreover, the added mass, damping and diffracted wave force in the x direction are assumed to be small and negligible. The equation of surge motion, therefore, can be expressed by

$$M_{11}\ddot{s}_1 = F_1 \qquad \text{Eqn. B.1}$$

or by using the coordinate system as a reference, Eqn. B.1 becomes

$$M\ddot{x} = F_1 \qquad \text{Eqn. B.2}$$

The symmetry of the hull with respect to the longitudinal centreplane leads to the decoupling of the vertical; plane (heave and pitch) from the horizontal plane (sway, roll and yaw) modes. Consequently, the equation of motion can be divided into two groups.

By expanding Eqn. 5.7 for heave and pitch modes, that is, j, k = 3 and 5, this can be written as

$$(M_{33} + A_{33})\ddot{s}_3 + B_{33}\dot{s}_3 + C_{33}s_3 + A_{35}\ddot{s}_5 + B_{35}\dot{s}_5 + C_{35}s_5 = F_3 \qquad \text{Eqn. B.3}$$

$$(M_{55} + A_{55})\ddot{s}_5 + B_{55}\dot{s}_5 + C_{55}s_5 + A_{53}\ddot{s}_3 + B_{53}\dot{s}_3 + C_{53}s_3 = F_5 \qquad \text{Eqn. B.4}$$

or by using the corresponding coordinate system, the above equations become

$$(M_{33} + A_{33})\ddot{z} + B_{33}\dot{z} + C_{33}z + A_{35}\ddot{\theta} + B_{35}\dot{\theta} + C_{35}\theta = F_3 \qquad \text{Eqn. B.5}$$

$$(I_5 + A_{55})\ddot{\theta} + B_{55}\dot{\theta} + C_{55}\theta + A_{53}\ddot{z} + B_{53}\dot{z} + C_{53}z = F_5 \qquad \text{Eqn. B.6}$$

Substituting Eqns. 5.14 and 5.15 into Eqn. B.4 for j, k = 3 and 5, the following equations are derived

$$[(M_{33} + A_{33})(-\omega^2) + B_{33}(-i\omega) + C_{33}]\bar{s}_3 + [A_{35}(-\omega^2) + B_{35}(-i\omega) + C_{35}]\bar{s}_5 \quad = \bar{F}_3$$

Eqn. B.7

$$[(I_5 + A_{55})(-\omega^2) + B_{55}(-i\omega) + C_{55}]\bar{s}_5 + [A_{53}(-\omega^2) + B_{53}(-i\omega) + C_{53}]\bar{s}_3 \quad = \bar{F}_5$$

Eqn. B.8

By substituting Eqns. 5.9 and 5.16 into Eqn. B.8 for k, j = 3 and 5 and arranging the right and left hand side of the above equations in terms of real and imaginary parts, the following matrix form of the resulting equation is obtained :

$$\begin{bmatrix} -\omega^2(M_{33}+A_{33})+C_{33} & -\omega^2 A_{35}+C_{35} & \omega B_{33} & \omega B_{35} \\ -\omega^2 A_{35}+C_{35} & -\omega^2(M_{55}+A_{55})+C_{55} & \omega B_{53} & \omega B_{55} \\ -\omega B_{33} & -\omega B_{35} & -\omega^2(M_{33}+A_{33})+C_{33} & -\omega^2 A_{35}+C_{35} \\ -\omega B_{53} & -\omega B_{55} & -\omega^2 A_{53}+C_{53} & -\omega^2(M_{55}+A_{55})+C_{55} \end{bmatrix} \times \begin{bmatrix} s_{3R} \\ s_{5R} \\ s_{3I} \\ s_{5I} \end{bmatrix} = \begin{bmatrix} F_{3R} \\ F_{5R} \\ F_{3I} \\ F_{5I} \end{bmatrix}$$

Eqn. B.9

or by using the index notation correspond to the coordinate system, Eqn. B.9 can be written as

$$\begin{bmatrix} -\omega^2(M_{33}+A_{33})+C_{33} & -\omega^2 A_{35}+C_{35} & \omega B_{33} & \omega B_{35} \\ -\omega^2 A_{35}+C_{35} & -\omega^2(I_5+A_{55})+C_{55} & \omega B_{53} & \omega B_{55} \\ -\omega B_{33} & -\omega B_{35} & -\omega^2(M_{33}+A_{33})+C_{33} & -\omega^2 A_{35}+C_{35} \\ -\omega B_{53} & -\omega B_{55} & -\omega^2 A_{53}+C_{53} & -\omega^2(I_5+A_{55})+C_{55} \end{bmatrix} \times \begin{bmatrix} z_R \\ \theta_R \\ z_I \\ \theta_I \end{bmatrix} = \begin{bmatrix} F_{3R} \\ F_{5R} \\ F_{3I} \\ F_{5I} \end{bmatrix}$$

Eqn. B.10

By expanding Eqn. 5.7 for sway, roll and yaw modes, that is, j, k = 2, 4 and 6, this can be written as

$$(M_{22} + A_{22})\ddot{s}_2 + B_{22}\dot{s}_2 + A_{24}\ddot{s}_4 + B_{24}\dot{s}_4 + A_{26}\ddot{s}_6 + B_{26}\dot{s}_6 = F_2$$

$$(M_{44} + A_{44})\ddot{s}_4 + B_{44}\dot{s}_4 + C_{44}s_4 + A_{42}\ddot{s}_2 + B_{42}\dot{s}_2 + A_{46}\ddot{s}_6 + B_{46}\dot{s}_6 = F_4$$

$$(M_{66} + A_{66})\ddot{s}_6 + B_{66}\dot{s}_6 + A_{62}\ddot{s}_2 + B_{62}\dot{s}_2 + A_{64}\ddot{s}_4 + B_{64}\dot{s}_4 = F_6$$

Eqn. B.11

Applying the corresponding coordinate system, motion Eqn. B.8 becomes

$$(M + A_{22})\ddot{y} + B_{22}\dot{y} + A_{24}\ddot{\phi} + B_{24}\dot{\phi} + A_{26}\ddot{\psi} + B_{26}\dot{\psi} = F_2$$

$$(I_4 + A_{44})\ddot{\phi} + B_{44}\dot{\phi} + C_{44}\phi + A_{42}\ddot{y} + B_{42}\dot{y} + A_{46}\ddot{\psi} + B_{46}\dot{\psi} = F_4$$

$$(I_6 + A_{66})\ddot{\psi} + B_{66}\dot{\psi} + A_{62}\ddot{y} + B_{62}\dot{y} + A_{64}\ddot{\phi} + B_{64}\dot{\phi} = F_6$$

Eqn. B.12

A similar procedure as in the coupled heave and pitch is implemented for the sway, roll and yaw, that is, k, j, = 2, 4 and 6, which yields the following matrix form of Eqn. B.12

$$\begin{bmatrix} -\omega^2(M_{22}+A_{22}) & -\omega^2 A_{24} & -\omega^2 A_{26} & \omega B_{22} & \omega B_{24} & \omega B_{26} \\ -\omega^2 A_{24} & -\omega^2(M_{44}+A_{44})+C_{44} & -\omega^2 A_{46} & \omega B_{24} & \omega B_{44} & \omega B_{46} \\ -\omega^2 A_{62} & -\omega^2 A_{44} & -\omega^2(M_{66}+A_{66})+C_{66} & \omega B_{62} & \omega B_{64} & \omega B_{66} \\ -\omega B_{22} & -\omega B_{24} & -\omega B_{26} & -\omega^2(M_{22}+A_{22}) & -\omega^2 A_{24} & -\omega^2 A_{26} \\ -\omega B_{24} & -\omega B_{44} & -\omega B_{46} & -\omega^2 A_{24} & -\omega^2(M_{44}+A_{44})+C_{44} & -\omega^2 A_{26} \\ -\omega B_{62} & -\omega B_{64} & -\omega B_{66} & -\omega^2 A_{62} & -\omega^2 A_{44} & -\omega^2(M_{66}+A_{66})+C_{66} \end{bmatrix} \times \begin{bmatrix} s_{2R} \\ s_{4R} \\ s_{6R} \\ s_{2I} \\ s_{4I} \\ s_{6I} \end{bmatrix} = \begin{bmatrix} F_{2R} \\ F_{4R} \\ F_{6R} \\ F_{2I} \\ F_{4I} \\ F_{6I} \end{bmatrix}$$

Eqn. B.13

or by using the index notation in conjunction with the coordinate system equation can be written as

$$\begin{bmatrix} -\omega^2(M_{22}+A_{22}) & -\omega^2 A_{24} & -\omega^2 A_{26} & \omega B_{22} & \omega B_{24} & \omega B_{26} \\ -\omega^2 A_{24} & -\omega^2(I_4+A_{44})+C_{44} & -\omega^2 A_{46} & \omega B_{24} & \omega B_{44} & \omega B_{46} \\ -\omega^2 A_{62} & -\omega^2 A_{44} & -\omega^2(I_6+A_{66})+C_{66} & \omega B_{62} & \omega B_{64} & \omega B_{66} \\ -\omega B_{22} & -\omega B_{24} & -\omega B_{26} & -\omega^2(M_{22}+A_{22}) & -\omega^2 A_{24} & -\omega^2 A_{26} \\ -\omega B_{24} & -\omega B_{44} & -\omega B_{46} & -\omega^2 A_{24} & -\omega^2(I_4+A_{44})+C_{44} & -\omega^2 A_{26} \\ -\omega B_{62} & -\omega B_{64} & -\omega B_{66} & -\omega^2 A_{62} & -\omega^2 A_{44} & -\omega^2(I_6+A_{66})+C_{66} \end{bmatrix} \times \begin{bmatrix} y_R \\ \phi_R \\ \psi_R \\ y_I \\ \phi_I \\ \psi_I \end{bmatrix} = \begin{bmatrix} F_{2R} \\ F_{2R} \\ F_{6R} \\ F_{2I} \\ F_{4I} \\ F_{6I} \end{bmatrix}$$

Eqn. B.14

2.0 MOTION PREDICTION OF OFFSHORE SUPPLY VESSELS

The first step in calculating the ship motions in a realistic irregular seaway is through its experience in regular sea waves. In this section, the prediction of heaving, pitching and rolling motions of the will be discussed.

2.1 Heaving Motion

For the equilibrium condition of the heaving motion, the equation of such motion is given by

$$a\ddot{z} + b\dot{z} + cz = F_0 \cos \omega t \qquad \text{Eqn. B.15}$$

where the solution is given by

$$z = e^{-vt}(C_1 \cos \omega_d t + C_2 \sin \omega_d t) + z_a \cos(\omega_e t - \varepsilon_2) \qquad \text{Eqn. B.16 (a)}$$

or

$$z = Ae^{-vt} \sin(\omega_d t - \beta) + z_a \cos(\omega_e t - \varepsilon_2) \qquad \text{Eqn. B.16 (b)}$$

with

z_a = amplitude of force motion ($z_a = z_{st}\mu_z$)
z_{st} = static heaving force ($z_{st} = F_o/c$)

μ_z = magnification factor

$$= \frac{1}{\sqrt{(1-\Lambda^2)^2 + 4\kappa^2\Lambda^2}}$$

Λ = tuning factor ($\Lambda = \omega_e/\omega_z$)

κ = non-dimensional damping factor ($\kappa = \nu/\omega_z$ with $\nu = b/2a$)

$\omega_z = (c/a)^{0.5}$

ε_2 = phase angle between the exciting force and the motion

$$= \tan^{-1}\left(\frac{2\kappa\Lambda}{1-\Lambda^2}\right)$$

The virtual mass a (the vessel mass plus added mass) is obtainable from the equation given by

Inertia force coefficient, $a = (\Delta + a_z)$

where

Δ = mass of vessel, and

$$a_z = \rho\frac{\pi}{2}\int_{-L/2}^{L/2} Cy^2(x)dx \qquad \text{Eqn. B.17}$$

where C is the coefficient for Lewis-form sections obtained from [1] as a function of the draught/beam ratio, and the area coefficient of the section as well as a function of circular frequency of oscillations. y(x) is the half-breadth of vessel at the waterline.

The damping coefficient which normally depends on the type of oscillatory motion, encountering frequency and the form of the vessel is given by

$$\text{Damping force coefficient, } b = \int_{-L/2}^{L/2}\left(\frac{\rho g\bar{A}^2}{\omega_e^3}\right)dx \qquad \text{Eqn. B.18}$$

where $\bar{A}$ is the amplitude ratio of radiated waves and heaving motion and can be obtained from [1].

The restoring force coefficient for heaving motion is given by

$$\text{Restoring force coefficient, } c = \rho g \int_{-L/2}^{L/2} 2y(x)\,dx \qquad \text{Eqn. B.19}$$

where y(x) is the half-breadth at section x.

The amplitude of the total exciting force, F_o, is obtained by integrating the buoyancy force of individual sections which is given by

$$\text{Total exciting force, } F_o = \left(2\rho g \zeta_a \int_{-L/2}^{L/2} y \cos k'x\,dx\right) \qquad \text{Eqn. B.20}$$

where

$k' = k\cos\mu$ (k is wave number and μ is the direction the vessel's heading in relation to the waves)

2.2 Pitching Motion

Unlike the heaving motion which is linear, the pitching motion is rotational about the transverse axis. The equation of motion for pitching in waves is given by

$$a\ddot{\theta} + b\dot{\theta} + c\theta = M_o \sin \omega_e t \qquad \text{Eqn. B.21}$$

and the solution is given by

$$\theta = Be^{-vt}\sin(\omega_d t + \gamma) + C\sin(\omega_e t - \varepsilon_2) \qquad \text{Eqn. B.22 (a)}$$

which for a steady state condition (when the first term dies out with time, t), is

$$\theta = \theta_a \sin(\omega_e t - \varepsilon_2) \qquad \text{Eqn. B.22 (b)}$$

where

θ_a = pitch angle ($\theta_a = \theta_{st}\mu_\theta$)

θ_{st} = static pitch angle ($\theta_{st} = M_o/c$)
μ_θ = magnification factor

$$= \frac{1}{\sqrt{(1-\Lambda^2)^2 + 4\kappa^2\Lambda^2}}$$

Λ = tuning factor ($\Lambda = \omega_e/\omega_\theta$)

κ = non-dimensional damping factor ($\kappa = \nu/\omega_\theta$ with $\nu = b/2a$)

$\omega_\theta = (c/a)^{0.5}$

$\varepsilon_2 =$ phase angle between the exciting force and the motion

$$= \tan^{-1}\left(\frac{2\kappa\Lambda}{1-\Lambda^2}\right)$$

The virtual mass moment of inertia for pitching is the vessel moment of inertia plus the added mass moment of inertia and is given by

Virtual mass moment of inertia $= I_{yy} + \delta I_{yy}$

where

$$I_{yy} \approx \rho\int_{-L/2}^{L/2} A(x)x^2\,dx \qquad \text{Eqn. B.23}$$

with A(x) the sectional area, and

$$\delta I_{yy} = \rho\frac{\pi}{2}\int_{-L/2}^{L/2} Cx^2y^2\,dx \qquad \text{Eqn. B.24}$$

with x the distance of each section from LCG and C, as heaving motion, obtainable from [1].

The damping coefficient for pitching can be obtained from

$$\text{Pitching moment coefficient, } b = \rho g^2\int_{-L/2}^{L/2}\left(\frac{\overline{A}^2}{\omega_e^3}\right)\xi\,d\xi \qquad \text{Eqn. B.25}$$

where

ξ = distance of individual strip from the LCG
$\overline{A}$ = as for heaving motion

The restoring moment coefficient can be expressed in the simple form as

$$\text{Restoring moment coefficient, } c = \rho g \int_{-L/2}^{L/2} x^2 y(x)\,dx = \rho g I_y \qquad \text{Eqn. B.26}$$

where I_y is the moment of inertia of the load waterplane area.

The amplitude of the exciting moment

$$M_o = 2\rho g \zeta_a \int_{-L/2}^{L/2} y(x) \sin(kx\cos\mu)\,dx \qquad \text{Eqn. B.27}$$

2.3 Rolling Motion

The equation of motion for rolling is analogous to that for pitching and is given by

$$a\ddot{\phi} + b\dot{\phi} + c\phi = M_o \sin\omega_e t \qquad \text{Eqn. B.28}$$

and the solution is given by

$$\phi = e^{-vt}(C\sin\omega_d t + D\sin\omega_d t) + \phi_a \sin(\omega_e t - \varepsilon_2) \qquad \text{Eqn.B.29 (a)}$$

which for a steady state condition (when the first term dies out with time, t), is

$$\phi = \phi_a \sin(\omega_e t - \varepsilon_2) \qquad \text{Eqn. B.29 (b)}$$

where

$$\phi_a = \frac{k\zeta_a}{\sqrt{(1-\Lambda^2)^2 + 4\kappa^2\Lambda^2}}$$

μ_ϕ = magnification factor

$$= \frac{1}{\sqrt{(1-\Lambda^2)^2 + 4\kappa^2\Lambda^2}}$$

Λ = tuning factor ($\Lambda = \omega_e/\omega_\phi$)

κ = non-dimensional damping factor ($\kappa = v/\omega_\theta$ with $v = b/2a$)

ω_ϕ = $(c/a)^{0.5}$

$\varepsilon_2 =$ phase angle between the exciting force and the motion

$$= \tan^{-1}\left(\frac{2\kappa\Lambda}{1-\Lambda^2}\right)$$

The virtual mass moment of inertia for rolling is the vessel moment of inertia plus the added mass moment of inertia and is given by

$$\text{Virtual mass moment of inertia} = \frac{\Delta}{g} k_{xx}''^{2} \qquad \text{Eqn. B.30}$$

where

k''_{xx} is the virtual radius of gyration of vessel and is often expressed as a fraction of the beam of the vessel and is normally in the range of 0.33 to 0.45 beam of vessel

The damping coefficient for rolling motion is given by

$$\text{Rolling moment coefficient, } b = \int_{-L/2}^{L/2} \frac{\rho g^2}{\omega_e^3}\left(\frac{B_n}{2}\right)^2 \overline{A}_\phi^2 \, d\xi \qquad \text{Eqn. B.31}$$

where

$$d_\phi = \left(\frac{\omega_e^2 B_n}{2g}\right)^2$$

with the values d_ϕ obtainable from [1] is a function of individual section coefficient β and S_n ($= B_n/2T_n$).

The restoring moment coefficient for the rolling motion is given by

$$\text{Restoring moment coefficient } c = \rho g \nabla \overline{GM_T} \qquad \text{Eqn. B.32}$$

where $\overline{GM_T}$ is the transverse metacentric height of vessel.

The exciting moment for rolling is given by

$$M_o = \frac{2}{3}\rho g k \zeta_a \sin\mu \int_{-L/2}^{L/2} \cos(kx\cos\mu) y^3 \, dx \qquad \text{Eqn. B.33}$$

3.0 A FAMILY OF SPECTRAL FORMS

Many spectra may be written in the following form,

$$S(\omega) = A\omega^{-p} \exp(-B\omega^{-q}) \qquad \text{Eqn. B.34}$$

and interest is in the moments of the spectrum, which are

$$m_n = \int_0^\infty S(\omega)\omega^n \, d\omega \qquad \text{Eqn. B.35}$$

or their ratios. Thus,

$$m_n = \int_0^\infty A\omega^{n-p} \exp(-B\omega^{-q}) d\omega \qquad \text{Eqn. B.36}$$

This may be identified with the form of the gamma function $\Gamma(x)$ which is written as

$$\Gamma(x) = \int_0^\infty y^{x-1} \exp(-y) dy \qquad \text{Eqn. B.37}$$

where

$y = B\omega^{-q}$, and

$$x = \frac{p-n-1}{q}$$

This gives

$$m_n = \frac{A}{qB^{(p-n-1)/q}} \Gamma\left(\frac{p-n-1}{q}\right) \qquad \text{Eqn. B.38}$$

Consequently, significant wave height

$$m_n = \frac{A}{qB^{(p-n-1)/q}}\Gamma\left(\frac{p-n-1}{q}\right) \qquad \text{Eqn. B.39}$$

Energy average period,

$$T_{-1} = \frac{2\pi m_{-1}}{m_0} = 2\pi B^{-1/q}\frac{\Gamma(p/q)}{\Gamma((p-1)/q)} \qquad \text{Eqn. B.40}$$

Average mean period,

$$T_1 \text{ or } T_{1/3} = \frac{2\pi m_0}{m_1} = 2\pi B^{1/q}\frac{\Gamma((p-1/q)}{\Gamma((p-2)/q)} \qquad \text{Eqn. B.41}$$

(also known as significant period and denoted by $T_{1/3}$)

Average zero crossing period,

$$T_2 \text{ or } T_z = 2\pi\left(\frac{m_0}{m_2}\right)^{1/2} = 2\pi B^{-1/q}\left[\frac{\Gamma\left(\frac{p-1}{q}\right)}{\Gamma\left(\frac{p-3}{q}\right)}\right]^{1/2} \qquad \text{Eqn. B.42}$$

Average crest to crest period,

$$T_4 \text{ or } T_c = 2\pi\left(\frac{m_2}{m_4}\right)^{1/2} = 2\pi B^{-1/q}\left[\frac{\Gamma\left(\frac{p-3}{q}\right)}{\Gamma\left(\frac{p-5}{q}\right)}\right]^{1/2} \qquad \text{Eqn. B.43}$$

Skewness,

$$\tau = \left(\frac{m_3}{m_2^{3/2}}\right) = \frac{q^{1/2}}{A}B^{(p-1)/2q}\left[\frac{\Gamma\left(\frac{p-3}{q}\right)}{\Gamma^{3/2}\left(\frac{p-5}{q}\right)}\right] \qquad \text{Eqn. B.44}$$

Broadness,

$$\varepsilon = 1 - \left[\frac{m_2^2}{m_0 m_4}\right]^{1/2} = 1 - \left[\frac{\Gamma^2\left(\frac{p-3}{q}\right)}{\Gamma\left(\frac{p-1}{q}\right)\Gamma\left(\frac{p-5}{q}\right)}\right]^{1/2} \qquad \text{Eqn. B.45}$$

Flatness,

$$\beta = \left(\frac{m_4}{m_2^2}\right) = \frac{q}{A} B^{(p-1)/q} \left[\frac{\Gamma\left(\frac{p-5}{q}\right)}{\Gamma^2\left(\frac{p-3}{q}\right)}\right] \qquad \text{Eqn. B.46}$$

In many cases, the period and significant wave height are considered known and the spectrum can be written as

$$S(\omega) = \frac{q}{16} H_{1/3}^2 \left(\frac{2\pi}{T_z}\right)^{p-1} \left[\frac{\Gamma\left(\frac{p-1}{q}\right)^{p-3}}{\Gamma\left(\frac{p-2}{q}\right)^{p-1}}\right]^{1/2} \omega^{-p} \exp\left\{-\left[\frac{\Gamma\left(\frac{p-3}{q}\right)}{\Gamma\left(\frac{p-1}{q}\right)}\right]^{1/2} \left(\frac{\omega T_z}{2\pi}\right)^{-q}\right\}$$

Eqn. B.47

or

$$S(\omega) = \frac{q}{16} H_{1/3}^2 \left(\frac{2\pi}{T_{1/3}}\right)^{p-1} \left[\frac{\Gamma\left(\frac{p-1}{q}\right)^{p-2}}{\Gamma\left(\frac{p-2}{q}\right)^{p-1}}\right] \omega^{-p} \exp\left\{-\left[\frac{\Gamma\left(\frac{p-2}{q}\right)}{\Gamma\left(\frac{p-1}{q}\right)}\right] \left(\frac{\omega T_z}{2\pi}\right)^{-q}\right\}$$

Eqn. B.48

and the peak is at

$$\omega_0 = \left(\frac{qB}{p}\right)^{1/q} \qquad \text{Eqn. B.49}$$

Most useful values of $\Gamma(x)$ may be found from

$$\Gamma(n + a/b) = \frac{a(a+b)}{b^n} \cdots\cdots \{a + b(n-1)\}\Gamma(a/b) \qquad \text{Eqn. B.50}$$

$\Gamma(1/4) = 3.625609908$ $\quad$ $\Gamma(3/2) = 0.5\pi^{1/2}$

$\Gamma(1/2) = \pi^{1/2}$ $\quad$ $\Gamma(7/4) = 0.919062527$

$\Gamma(3/4) = 1.225416702$ $\quad$ $\Gamma(2) = 1$

$\Gamma(1) = 1$ $\quad$ $\Gamma(5/2) = 0.25\pi^{1/2}$

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APPENDIX C

EXPERT SYSTEM SHELL - LEONARDO

1.0 INTRODUCTION

Leonardo is one of the leading British-produced expert system shells. It is developed and supported by *Software Directions* and has been used to produce a range of expert system applications in fields as diverse as brain scanning, scheduling in robotics manufacture, and export control. *Leonardo* runs on *IBM XT* or *AT* compatibles with 512K, and *MA* or *PC Dos* 2.00 or above. In this study, level 3 of version 3.20 of the product was used.

2.0 FEATURES OF LEONARDO

There are two main forms of knowledge representation in Leonardo : production rules and frames. The rules represent procedural knowledge and are used to assign values to text, numeric and list objects; invoke screens; and execute procedures written in Leonardo's procedural programming language.

Backward and forward chaining is supported, but the default inferencing method is backward chaining with opportunistic forward chaining, to make maximum use of data at the time that it is input. Essentially this means that the system looks for rules with the goal object as their final conclusion and attempts to satisfy them in a depth-first manner, but that is also propagates the immediate results of obtaining a value for any object. This is typically more efficient than pure backward chaining, but still allows the HOW? and WHY? retracing facilities which expert systems users expect. The inference mechanism allows rules of the form if x is true or y is true then x is true to be evaluated successfully if either x or y is true, rather than, as formerly, failing if x is false while y is true. This provides for greater freedom of expression in rules and can reduce the number of rules needed. Iterative processing of rules is available, as is uncertainty in rule processing, using either Bayesian probabilities or certainty factors. With *Leonardo*, applications can be developed in stages, since rules can be written and tested in discrete sets and subsequently merged.

A frame is associated with each object used in a rule. The information held in a frame specifies the source of the object's value (either input by the application user or, for example, calculated) the certainty of its value (s), and any associated text such as prompts and explanations. Objects can be organised into classes with user-defined attributes. For example , a class of objects called 'information sources' might have attributes such as 'source name', 'type of coverage', and 'cost'. Multiple levels of inheritance are supported, with no limit on the number of levels. Facilities for manipulating class objects include creating class attributes and members at run time, and updating the value of attributes.

Leonardo has an extensive and relatively powerful procedural programming language, with functions for performing calculations, handling strings, lists, arrays, and dates; outputting to the screen; accepting input; and file handling. Provision is also made for calls to external programs written in languages such as C, Fortran and Pascal, allowing Leonardo to interact with existing applications, as a front end for example. Interfaces to files created with proprietary software such as Lotus 1-2-3 and dBase are available as optional toolkits. Other toolkits include a screen designer, and two packages of mathematical and statistical functions respectively which extend the procedural programming language.

3.0 DEVELOPMENT SUPPORT

Leonardo begins by displaying a top-level menu offering functions for handling knowledge bases such as load, copy and save; editing and printing rules and objects; checking and compiling knowledge bases; and running them. Several utilities such as importing and exporting files are also offered.

The editor is easy to use. Objects are accessed for editing via an Object Directory, a list of objects generated by rule-checking. Object values are also listed in the directory after a knowledge base has been consulted, which is very helpful when testing a knowledge base. Functions for checking the usage of objects and copying, selecting, sorting and printing them are available.

User input can be handled by using prompts and menus which are very easy and quick to create. The procedural language can be used to deal with less structured input. The ability to set up validation and to attach prompts and explanatory text to objects simply by completing frame attributes is a boon to prototyping. The limit on the number of menu items is rather arbitrary, being dependent on the size of the screen. The screen painter toolkit provides functions for customising screens, for example, multiple menus can be defined and screens can be linked and overlaid.

There are several options for checking and compiling rules and objects; a full trace, summary of checking only, a quick check with limited reporting, and an incremental check of previously unchecked objects. This last option deals with one of the major problems in previous versions of Leonardo, when it could take as long to check a rulebase as actually to write and test it. Incremental checking works fairly well, though one problem relating to the assignment of the object type was encountered and could only be solved by running a full check. Another option, for purging unused rules, has cause Leonardo to hang on occasion. Extensive trace facilities to assist debugging are available and are invoked by specifying them in the main ruleset. Additionally, at the end of a consultation, it is possible to step back through sections of a ruleset and examine object values. Overall, the facilities for testing and debugging are good.

4.0 CONSULTATION SUPPORT

It is easy to consult Leonardo applications from the program and input can be limited to menu selections, depending on the application. Some users would, however, probably need more explanation of available functions than that offered by the somewhat cryptic function key labels. The default screen layouts are reasonably attractive and would certainly suffice for prototyping purposes. As mentioned above, toolkits for custom-designing screens and creating graphical displays are available. The screen designer toolkit includes a hypertext facility which can be used to open multiple windows of related text. Text held in ASCII files can also be displayed as hypertext without the need to incorporate it permanently into the knowledge base, providing easy maintenance.

Extented explanations can be incorporated in the knowledge base, so the user can find out why particular information is required. Where no explanation has been provided, a clear message informing the user is displayed. Information can be volunteered, but only by typing in values against objects in the Object Directory; most users would probably be confused by this since all objects, rather than just those requiring user input, are listed. What-if?s are catered for by a function which allows the user to step back through the ruleset and change values though, the presentation of this is somewhat confusing and unfriendly. At the end of a consultation, the user can review it either by displaying a session log or by copying the log to file.

5.0 DOCUMENTATION

The documentation for Leonardo comprises a user guide, reference manual and a tutorial. Both manuals are comprehensive, well organised, and clearly written. Their only real weakness is the rather sketchy indexes. Another minor criticism is that the documentation relating to new features in version 3.20 is published as an appendix to the reference manual rather than integrated into the relevant sections. Brief help is available for every development function except the editor, which novices would probably need.

There is a paper-based tutorial which demonstrates the essential features of Leonardo. The appendix to the tutorial covering debugging by using forward and backward chaining is not very clear and would certaintly mystify some users. A range of demonstration applications is provided, though some need more up-front explanation in order to be fully effective.

6.0 CONCLUSION

The range of features offered by Leonardo amounts to a powerful package for expert system development at an affordable price. The ability to organise taxonomic knowledge in classes provides for concise and yet comprehensive representation of the type of knowledge needed to support an online business information selector. Leonardo's frame structure offers a quick and simple method of controlling how objects are handled, both in rules and on screen. The procedural programming language gives the developer much more flexibility than could be provided by rules alone. Finally, the hypertext capability could be particular useful for displaying additional information about online sources. A sample of expert system programming using Leonardo is given at the end of this section.

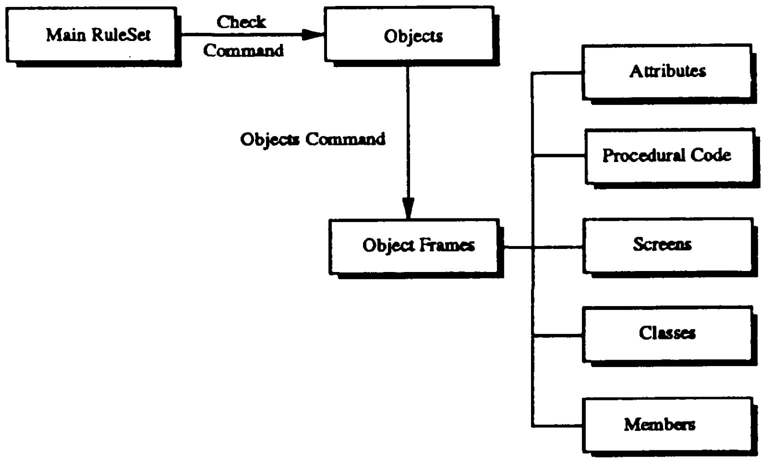

Fig. C.1 Structure of the Knowledge Base

Name : {protected}

LongName :

Type : {protected}

Value : {protected}

Certainty : {protected}

DerivedFrom : {protected}

DefaultValue :

FixedValue :

AllowedValue :

ComputeValue :

OnError :

QueryPrompt :

QueryPreface :

Expansion :

Commentary :

Introduction :

Conclusion :

Fig. C.2 Slots Available in Object Frame

SAMPLE OF EXPERT SYSTEM PROGRAMMING
(Seakeeping Analysis of Offshore Supply Vessel)

Rules

```
/* Seakeeping Characteristics of Offshore Supply Vessels

if start is yes
use screen1;
input_data is known

if input_data is known
and Hz > 0.0
and T1 > 0.0
and aot > 0.0
and speed > 0.0
then run seakeeposv(L, B, d, T, disp, GM,  Hz, T1, aot, speed, lcg(6), ac(6),
                    B(6), sm(6), st, hav, veh, ach, pav, vep, acp, haw, vew,
                    acw, avw, ahh, pah, rar, pam, vem, acm);
seachaosv is done

seek seachaosv
```

Objective Frame

```
         Name : Hz
     LongName : Wave Height in m
         Type : Real
        Value : {you input a value}
 AllowedValue : > 0.0
 ComputeValue :
  QueryPrompt : What is the wave height in metres?
 QueryPreface :
    Expansion :
   Commentary :
 Introduction :
   Conclusion :
```

Procedural Frame

Name : seakeeposv
LongName : Evaluation of Seakeeping Characteristics of OSV
Type : Procedure
AcceptsReal : L, B, D, T, disp, GM, Hz, T1, aot, speed, lcg(6), ac(6), B(6), sm(6), st
AcceptsText :
AcceptsList :
ReturnsReal : hav, veh, ach, pav, vep, acp, haw, vew, acw, avw, ahh, pah, rar, pam, vem, acm
LocalReal : f(6), bt(6), bn(6), cq(6), ad(60, an(60, dc(6), rc(6), ac(6), fo(6), amp(6), dcp(6), rcp(6), fop(6), drr(6) apr(6), bnr(6), frr(6), we(10), ww(10), wz(10), kk(10), rcpp(10), kf(10), tf(10), za(10), ampp(10), dcpp(10), fopp(10), fopt(10), wp(10),tp(10), kp(10), kfp(10), zp(10), foh(10), dch(10), amh(10), Tz(10), arr(10), brr(10), fot(10), rch(10), ftr(10), frt(10), amr(10), wr(10) tr(10), kr(10), kfr(10), zr(10), br(10), sg, k, i
Body :

```
/* Start of Calculations

repeat k(1,9)
we(k) = 0.2 * k

if ((speed eq 0.0) or (aot eq 90.0)) then ww(k) = we(k)
if ((speed gt 0.0) and (aot gt 90)) then
ww(k) = (1.0 - (sqrt(1.0 - (4.0 * speed * 0.514 * cos(aot/57.3) *we(k)/9.81))))/(&
        2 * speed * 0.514 * cos(aot/57.3)/9.81)
endif

Tz(k) = 2 * 3.142/(ww(k))
kz(k) = 4 * ((3.142)^2)/(((Tz(k))^2) * 9.81

repeat i(1,6)

/* Estimation of Coefficients for Heave, Pitch and Roll for Each Section

f(i)  = ((we(k)^2) * B(i)/(2 * 9.81)
```

```
bt(i)  = B(i)/T
bn(i) = ac(i)/ (B(i) * T)
br(i)  = B(i)/(2 * T)

if bn(i) lt 0.5 then
cq(i) = 0.0
ad(i) = 0.0
endif

if ((bn(i) ge 0.5) and (bn(i) lt 0.6) and (bt(i) le 2.0)) then
cq(i) = 1.3443 - 1.692 * f(i) + 0.7738 * ((f(i))^2)
ad(i) = 0.10857 + 1.0857 * f(i) - 0.32143 * ((f(i)^2)
endif

if ((bn(i) ge 0.6) and (bn(i) lt 0.8) and (bt(i) le 2.0)) then
cq(i) = 1.1029 - 1.2702 * f(i) + 0.59524 * ((f(i))^2)
ad(i) = 0.10857 + 1.0857 * f(i) - 0.32143 * ((f(i)^2)
endif

if ((bn(i) ge 0.8) and (bn(i) lt 0.9) and (bt(i) le 2.0)) then
cq(i) = 1.1564 - 1.1991 * f(i) + 0.611 * ((f(i))^2)
ad(i) = 0.17429 + 0.7667 * f(i) - 0.39881 * ((f(i)^2)
endif

if ((bn(i) gt 0.8) and (bt(i) gt 2.0)) then
cq(i) = 1.6342 - 2.7350 * f(i) + 2.8793 * ((f(i))^2)
ad(i) = 0.080 + 1.1980 * f(i) - 0.3660 * ((f(i)^2)
endif

if ((bn(i) ge 0.5) and (bn(i) lt 0.6) and (bt(i) gt 2.0)) then
cq(i) = 1.4271 - 1.4506 * f(i) + 0.6220 * ((f(i))^2)
ad(i) = 0.03428 + 1.3571 * f(i) - 0.32143 * ((f(i)^2)
endif

if ((bn(i) ge 0.6) and (bn(i) lt 0.8) and (bt(i) gt 2.0)) then
cq(i) = 1.4186 - 1.5464 * f(i) + 0.69643 * ((f(i))^2)
ad(i) = 0.03428 + 1.3571 * f(i) - 0.32143 * ((f(i)^2)
endif

if br(i) lt 0.5 then drr(i) = 0.0

if (br(i) ge 0.5) and (br(i) lt 0.8)) then
```

```
drr(i) = 1.1177 - 2.7847 * bn(i) + 7.6555 * ((bn(i))^2)
endif

if ((br(i) ge 0.8) and (br(i) lt 1.0) and ((bn(i) lt 0.48)) then
drr(i) = 0.12931 + 2.9287 * bn(i) - 5.6459 * ((bn(i))^2)
endif

if ((br(i) ge 0.8) and (br(i) lt 1.0) and ((bn(i) ge 0.48)) then
drr(i) = 1.2835 - 6.0683 * bn(i) + 7.1501 * ((bn(i))^2)
endif

if ((br(i) ge 1.0) and (br(i) lt 1.4) and ((bn(i) lt 0.77)) then
drr(i) = 0.46732 + 1.0406 * bn(i) - 2.0347 * ((bn(i))^2)
endif

if ((br(i) ge 1.0) and (br(i) lt 1.4) and ((bn(i) ge 0.77)) then
drr(i) = -4.6667 + 6.9000 * bn(i) - 1.3300 * ((bn(i))^2)
endif

if br(i) ge 1.4 then
drr(i) = 0.41979 + 1.9530 * bn(i) - 2.2322 * ((bn(i))^2)
endif

an(i) = 1.025 * 3.142 * cq(i) * ((B(i))^2) * sm(i)/8
dc(i) = 1.025 * ((9.81)^2) * ((ad(i))^2) * sm(i)/((we(k))^3)
rc(i) = 1.025 * 9.81 * B(i) * sm(i)
fo(i) = B(i) * cos(kz(k) * lcg(i) * cos(aot/57.3))) * sm(i)

amp(i) = an(i) * ((lcg(i))^2) * sm(i)
dcp(i) = dc9i) * ((lcg(i))^2) * sm(i)
rcp(i) = 1.025 * lcg(i) * (sin(kz(k) * lcg(i) * cos(aot/57.3))) * sm(i)/((we(k))^3
frr(i) = (fo(I)/2) * ((B(i))^2)
endrep

/* Evaluations of Heave Coefficients

amh(k)= st * (an(1) + an(2) + an(3) + an(4) + an(5) +an(6))/3
dch((k)= st * (dc(1) + dc(2) + dc(3) + dc(4) + dc(5) +dc(6))/3
rch(k) = st * (rc(1) + rc(2) + rc(3) + rc(4) + rc(5) +rc(6))/3
foh(k) = st * (fo(1) + fo(2) + fo(3) + fo(4) + fo(5) +fo(6))/3
```

```
/* Evaluation of Pitching Coefficients

ampp(k)  = st * (amp(1) + amp(2) + amp(3) + amp(4) + amp(5) +amp(6))/3
dcpp((k) = st * (dcp(1) + dcp(2) + dcp(3) + dcp(4) + dcp(5) +dcp(6))/3
rcpp(k)  = st * (rcp(1) + rcp(2) + rcp(3) + rcp(4) + rcp(5) +rcp(6))/3
fopp(k)  = st * (fop(1) + fop(2) + fop(3) + fop(4) + fop(5) +fop(6))/3
fopt(k)  = 9.81 * 1.025 * Hz * fopp(k)


/* Evaluation of Rolling Coefficients

amr(k)  = disp * ((0.350 * beam)^2)
arr(k)  = 9.81 * disp * GM
brr(k)  = st * (bnr(1) + bnr(2) + bnr(3) + bnr(4) + bnr(5) +bnr(6))/3
ftr(k)  = st * (frr(1) + frr(2) + frr(3) + frr(4) + frr(5) +frr(6))/3
frt(k)  = (9.81 * 1.025 * kz(k) * Hz * sin(aot/57.3) * ftr(k))/3


/* Evaluation of Heaving  Period  & Amplitude

wz(k)  = sqrt((rch(k)/(amh(k) + disp)))
tf(k)  = we(k)/wz(k)
kk(k)  = dch(k)/(2 * wz(k) * (amh(k) + disp))
kf(k)  = sqrt((1 - (tf(k) * tf(k)))^2) + (4 * ((kk(k))^2) * ((tf(k))^2)))
za(k)  = abs(fot(k)/(rch(k) * kf(k)))


/* Evaluation of Pitching Period & Amplitude

wp(k)  = sqrt((rcpp(k)/(ampp(k) + disp)))
tp(k)  = we(k)/wp(k)
kp(k)  = dcpp(k)/(2 * wp(k) * (ampp(k) + disp))
kfp(k) = sqrt((1 - (tp(k) * tp(k)))^2) + (4 * ((kp(k))^2) * ((tp(k))^2)))
zp(k)  = abs(fopt(k)/(rcpp(k) * kfp(k)))


/* Evaluation of Rolling Period & Amplitude

wr(k)  = sqrt((arr(k)/(amr(k) + disp)))
tr(k)  = we(k)/wr(k)
kr(k)  = brr(k)/(2 * wr(k) * (amr(k) + disp))
kfr(k) = sqrt((1 - (tr(k) * tr(k)))^2) + (4 * ((kr(k))^2) * ((tr(k))^2)))
```

```
zr(k)   = abs(frt(k)/(arr(k) * kr(k)))
endrep


/* Spectral Analysis

repeat k(1,9)
ww(k) = 0.2 * k

if ww(k) le 5.24/(T1 * 1.073) then
sg = 0.07
else
sg = 0.09
endif

yy(k) = exp(-(((0.191 * ww(k) * (1.073 * T1)) - 1)/(sqrt(2) * sg))^2
sw(k) = 155 * ((Hz)^2) * ((3.3)^yy(k)) * (exp(-(944/(((1.073 * T1)^4) * &
        ((ww(k))^4)))/(((1.073 * T1)^4) * (ww(k))^5))
endrep


/* Evaluation of Wave Motions

mw1 = 0.2 * sw(1) + sw(2) * 4 + sw(3) * 2 + sw(4) * 4 + sw(5) * 2 +sw(6) * &
      4 + sw(7) * 2 + sw(8) * 4 + sw(9)
mw2 = 0.2 * (sw(1) * ((ww(1))^2) + sw(2) * ((ww(2))^2) * 4 + sw(3) * ((    &
      ww(3))^2) * 2 + sw(4) * ((ww(4))^2) * 4 + sw(5) * ((ww(5))^2) * 2  &
      + sw(6) * ((ww(6))^2) * 4 + sw(7) * ((ww(7))^2) * 2 + sw(8) * ((     &
      ww(8))^2) * 4 + sw(9) * ((ww(9))^2))
mw4 = 0.2 * (sw(1) * ((ww(1))^4) + sw(2) * ((ww(2))^4) * 4 + sw(3) * ((    &
      ww(3))^4) * 2 + sw(4) * ((ww(4))^4) * 4 + sw(5) * ((ww(5))^4) * 2  &
      + sw(6) * ((ww(6))^4) * 4 + sw(7) * ((ww(7))^4) * 2 + sw(8) * ((     &
      ww(8))^4) * 4 + sw(9) * ((ww(9))^4))

erw  = (mw1 * mw4 - ((mw2)^2))/(mw1 * mw4)
avw  = 1.253 * (sqrt (mw1)) * (sqrt(1 - ((erw)^2)))
haw  = 2.000 * (sqrt (mw1)) * (sqrt(1 - ((erw)^2)))
vew  = 2.000 * (sqrt (mw2)) * (sqrt(1 - ((erw)^2)))
acw  = 2.000 * (sqrt (mw4)) * (sqrt(1 - ((erw)^2)))

repeat k(1,9)
```

```
ww(k) = 0.2 * k

if ((speed eq 0.0) or (aot eq 90.0)) then ww(k) = we(k)
if ((speed gt 0.0) and (aot gt 90)) then
ww(k) = (1.0 - (sqrt(1.0 - (4.0 * speed * 0.514 * cos(aot/57.3) * we(k)/9.81))))/&
          (2 * speed * 0.514 * cos(aot/57.3)/9.81)
endif

swe(k)  = sw(k)/(sqrt(1 - ((4 * we(k) * 0.514 * speed/9,81) * cos(aot/57.3))))
swh(k)  = swe(k) * ((za(k)/(Hz/2))^2
swp(k)  = swe(k) * ((zp(k) * 57.3)/(Hz/2))^2)
swm(k) = swe(k) * ((zr(k) * 57.3)/(Hz/2))^2)
endrep


/* Evaluation of Heaving Motions

mh1 = 0.2 * swh(1) + swh(2) * 4 + swh(3) * 2 + swh(4) * 4 + swh(5) * 2 &
        +swh(6) * 4 + swh(7) * 2 + swh(8) * 4 + swh(9)
mh2 = 0.2 * (swh(1) * ((we(1))^2) + swh(2) * ((we(2))^2) * 4 + swh(3)    &
        * ((    we(3))^2) * 2 + swh(4) * ((we(4))^2) * 4 + swh(5) * ((       &
        we(5))^2) * 2 + swh(6) * ((we(6))^2) * 4 + swh(7) * ((we(7))^2)   &
        * 2 + swh(8) * ((we(8))^2) * 4 + swh(9) * ((we(9))^2))
mh4 = 0.2 * (swh(1) * ((we(1))^4) + swh(2) * ((we(2))^4) * 4 + swh(3)    &
        * ((    &we(3))^4) * 2 + swh(4) * ((we(4))^4) * 4 + swh(5) *         &
        ((we(5))^4) * 2 + swh(6) * ((we(6))^4) * 4 + swh(7) * ((we(7))^    &
        4) * 2 + swh(8) * ((we(8))^4) * 4 + swh(9) * ((we(9))^4))

err    = (mh1 * mh4 - ((mh2)^2))/(mh1 * mh4)
ahh   = 1.253 * (sqrt (mh1)) * (sqrt(1 - ((err)^2)))
hav   = 2.000 * (sqrt (mh1)) * (sqrt(1 - ((err)^2)))
veh   = 2.000 * (sqrt (mh2)) * (sqrt(1 - ((err)^2)))
ach   = 2.000 * (sqrt (mh4)) * (sqrt(1 - ((err)^2)))


/* Evaluation of Pitching Motions

mp1 = 0.2 * swp(1) + swp(2) * 4 + swp(3) * 2 + swp(4) * 4 + swp(5) * 2 &
        +swp(6) * 4 + swp(7) * 2 + swp(8) * 4 + swp(9)
mp2 = 0.2 * (swp(1) * ((we(1))^2) + swp(2) * ((we(2))^2) * 4 + swp(3)    &
        * ((    we(3))^2) * 2 + swp(4) * ((we(4))^2) * 4 + swp(5) * ((       &
        we(5))^2) * 2 + swp(6) * ((we(6))^2) * 4 + swp(7) * ((we(7))^2)   &
```

```
          * 2 + swp(8) * ((we(8))^2) * 4 + swp(9) * ((we(9))^2))
mp4 = 0.2 * (swp(1) * ((we(1))^4) + swp(2) * ((we(2))^4) * 4 + swp(3)    &
          * ((    &we(3))^4) * 2 + swp(4) * ((we(4))^4) * 4 + swp(5) *    &
          ((we(5))^4) * 2 + swp(6) * ((we(6))^4) * 4 + swp(7) * ((we(7))^    &
          4) * 2 + swp(8) * ((we(8))^4) * 4 + swp(9) * ((we(9))^4))

erp  = (mp1 * mp4 - ((mp2)^2))/(mp1 * mp4)
pah  = 1.253 * (sqrt (mp1)) * (sqrt(1 - ((erp)^2)))
pav  = 2.000 * (sqrt (mp1)) * (sqrt(1 - ((erp)^2)))
vep  = 2.000 * (sqrt (mp2)) * (sqrt(1 - ((erp)^2)))
acp  = 2.000 * (sqrt (mp4)) * (sqrt(1 - ((erp)^2)))


/* Evaluation of Rolling Motions

mr1 = 0.2 * swm(1) + swm(2) * 4 + swm(3) * 2 + swm(4) * 4 + swm(5) * 2 &
          +swm(6) * 4 + swm(7) * 2 + swm(8) * 4 + swm(9)
mr2 = 0.2 * (swm(1) * ((we(1))^2) + swm(2) * ((we(2))^2) * 4 + swm(3)    &
          * ((    we(3))^2) * 2 + swm(4) * ((we(4))^2) * 4 + swm(5) * ((    &
          we(5))^2) * 2 + swm(6) * ((we(6))^2) * 4 + swm(7) * ((we(7))^2)    &
          * 2 + swm(8) * ((we(8))^2) * 4 + swm(9) * ((we(9))^2))
mr4 = 0.2 * (swm(1) * ((we(1))^4) + swm(2) * ((we(2))^4) * 4 + swm(3)    &
          * ((    &we(3))^4) * 2 + swm(4) * ((we(4))^4) * 4 + swm(5) *    &
          ((we(5))^4) * 2 + swm(6) * ((we(6))^4) * 4 + swm(7) * ((we(7))^    &
          4) * 2 + swm(8) * ((we(8))^4) * 4 + swm(9) * ((we(9))^4))

erm  = (mr1 * mr4 - ((mr2)^2))/(mr1 * mr4)
rar  = 1.253 * (sqrt (mr1)) * (sqrt(1 - ((err)^2)))
pam  = 2.000 * (sqrt (mr1)) * (sqrt(1 - ((err)^2)))
vem  = 2.000 * (sqrt (mr2)) * (sqrt(1 - ((err)^2)))
acm  = 2.000 * (sqrt (mr4)) * (sqrt(1 - ((err)^2)))

return
```

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4. Halstead, R., 'Develop Advanced Expert Systems', Byte, Vol. 15, No. 1, 1990.

5. Vedder, R.G., 'PC- Based Expert System Shells : Some Desirable and Less Desirable Characteristics', Expert Systems, Vol. 6, No.1, 1989.

APPENDIX D

BIBLIOGRAPHY ON THE APPLICATION OF EXPERT SYSTEMS IN SHIP DESIGN

1. Sekimoto, T., Shimizu, K. and Koyama, T., 'An Object Oriented Tool for the Preliminary Design of Ships', Journal of Society of Naval Architects of Japan, 1990.

   In building a computer-aided design system, it is necessary to develop a suitable model for representing design processes that determine redesigning strategies. In this paper, the design object is described as a combination of a data structure and a set of constraints on related design parameters. The design process is represented by IF-THEN rules which reflect a skilful engineer's design know how. Some application results of the basic design of ships are presented to demonstrate the system.

2. Welsh, M., Buxton, I.L., and Hills, W., 'The Application of an Expert System to Ship Concept Design Investigations', Trans. RINA, Vol. 133, 1990.

   This paper describes how recent developments in computing technology can be adapted to improve the methods used to support concept design investigations. Particular attention is given to the application of an expert system to ship design A unique expert system is described which is particularly effective in a design environment where there are large number of variables and parameters and where spatial considerations are fundamental to the design process. A review of the main design considerations for container ships is given in which the complex nature of the design problem imposed by the requirement to satisfy a broad range of operations and technical considerations suggest that significant benefits are to be gained by utilising an expert system to support design studies. Two examples are given to illustrate how expert system can be applied during the development of a container ship design.

3. Schmidt, F.A. and Curran, E.P., 'The Application of IKBS to Ship Operation, Ship Evaluation and Ship Design', NAV '88 - WEMT '88 Symposium, Italy, 1988.

The affinity between operation/design and planning in the context of AI research is used to investigate the application of IKBS systems to ship operation and mission-orientated ship design. Instead of turning 'operational data' into information and using it in an algorithmic procedure, as is the case of conventional computing, the interaction between operation and mission-oriented design treated as a knowledge engineering problem, that is a heuristic procedure is used in an attempt to find an 'improve solution'. Rather than using one of the available AI languages, an Expert System Shell in conjunction with an IBM Compatible PC is used to build the IKBS system. Advantages/disadvantages of this approach are briefly discussed. The development of rules which eventually constitute the system is outlined. The system is then applied to conceptual mission-orientated ship design, and the system's use during evaluation is also outlined. Pending work to extend the knowledge base and the application of the system is indicated, and possible economic benefits to users are described.

4. Duffy, A.H.B. and MacCallum, K.J., 'Computer Representation of Numerical Expertise for Preliminary Ship Design', Marine Technology, Vol. 26, No. 4, 1989.

This paper examines work on an examination system, DESIGNER, used to carry out design session evaluations, using a warship design model. By this examination and insights gained from it an enhanced interactive numerical design system is developed. Using a bulk carrier design model, the paper presents a worked example illustrating the use of the new numerical knowledge techniques. It is considered that they could usefully contribute to any interactive numerical design system aiming to optimise the uses of expertise.

5. Akagi, S., 'Expert System for Engineering Design Based on Object Oriented Knowledge Representation Concept', Artificial Intelligence in Design - Pham, D.T. (Editor), Springer-Verlag Ltd., London, 1991.

This paper describes an objected-oriented knowledge-based system for preliminary ship design. The model for the design process is constructed using networks composed of knowledge elements, that is constraints, which are modularly represented as objects. This modelling results in determining of design variables in a flexible manner during the design process. The system also includes diagnostic functions in order to improve the original design model. The system was encoded in Common LISP, which was combined with FORTRAN programs for numerical computations and graphics. Examples of application to the preliminary design of a bulk carrier and a marine power plant selection is presented in this paper.

6. Ohitsubo, H. and Kitamura, M., 'Structural Design of a Mid-Ship Section using an Expert System', Journal of Society of Naval Architects of Japan, 1988 (in Japanese).

An expert system written in LISP is applied to a bulk carrier with emphasis on the structural design of the midship section. An optimisation technique is included to obtain the required longitudinal strength of the midship section in which the minimum weight is chosen to be an objective. This paper also demonstrates the procedure of redesigning the midship section from the requirements such as deadweight and the ship's speed in order to check the efficiency of the system. The midship section is compared with one having the same principle requirements.

7. Van Hees, M., 'QUAESTOR - A Knowledge-Based System for Computations in Preliminary Ship Design', Proceedings of Practical Design of Ships and Mobile Units, Newcastle, 1992.

The system, QUAESTOR, presented in this paper enables naval architects to integrate a large number of empirical calculation methods (in fact numerical design rules and their validities) and associated data (text and numbers) into a single database. This database or knowledge base can be used by the same system to perform calculations required in the preliminary design of ships. QUAESTOR offers facilities for the building and maintaining of knowledge bases and solving of any computational problem which fits in with the knowledge. For this purpose the network database concept, a bi-directional chaining strategy of reasoning and linear programming techniques are used. The input data required to solve a problem are provided by the user during a dialogue session. By means of the input provided and the approval of suggestions made by the system, the user controls the way the problem is solved. Example of application is demonstrated via the design of propellers for a high speed craft.

8. Akagi, S. and Fujita, K., 'Building an Expert System for Basic Ship Design', Journal of Society of Naval Architects of Japan, 1987 (in Japanese).

The design process is understood as determining the design parameters and the inter-relationship. An expert system built on the above concept provides the following functions : i) flexible model building and easy modification; ii) effective diagnosis of the design process by using rule-based knowledge representation; iii) hybrid function with both numerical computations and symbolic treatments of the design knowledge by coupling the systems programmed with LISP and FORTRAN languages. The system's validity and effectiveness was using a bulk carrier.

9. Perakis, A.N. and Dillingham, J.T., 'The Application of Artificial Intelligence Techniques in Marine Operations', SNAME International Symposium on Ship Operations Management and Economics, New York, 1987.

The problem of how to best apply the tools of Artificial Intelligence and Expert System (AI/ES) to assist in the solution of several important marine operations problems is addressed. An introduction of AI and ES technology is first presented, including an overview and history, a review of recommended readings, a discussion of when a problem is an appropriate candidate for AI/ES application, ES development tools, and estimates of their associated costs. A cost/benefit analysis of several potential applications in marine operations is conducted. One of these applications, namely that of container stowage, is examined in detail. Several conclusions from the above research are finally presented.

10. Shimuzu, K., 'Expert System for Subdivision Design of Tankers', Journal of Society of Naval Architects, Japan, 1987.

It is difficult to perform the subdivision design of tanker automatically because of a lot of restrictions such as total tank capacity, limitation of each tank size, trim, strength, etc. must be considered simultaneously. In this paper, an expert system prototype was built to assist a designer to perform the above task. The system composed of three subsystems which include production system, frame system and user interface system. The production system controls the basic loop of evaluation and redesign while the frame system supports powerfully redesign with automatic recalculation of related parameters. It was shown that the expert system could satisfactorily design the subdivision of conventional tankers from 100,000 dwt to 240,000 dwt automatically with satisfaction.

11. Akagi, S., Tanaka, T. and Kubonishi, H., 'An Expert CAD System for the Design of Marine Power Plants Using Artificial Intelligence', International Journal of Society of Mechanical Engineers (Japan), Vol. 31, 1988.

An expert CAD system is developed for the design of marine power plants using Artificial Intelligence (AI) concept. Firstly, the design process is discussed generally from the view point of applying AI technique effectively to the design process. It is found that a hybrid-type expert CAD system coupled with the AI technique and the design optimisation method is most effective for this type of CAD system. The system architecture of the developed CAD system consists of the knowledge base for the design rules, the frame-type data base of the plant machinery, and the mathematical optimisation process. through system execution, it is ascertained that the system is effective not only as a tool for plant design but also as a tool for instructing inexperienced designers.

12. Fjellttelm, R., 'An Expert System for SESAM - 69 Program Selection', Norwegian Maritime Research, Vol. 12, 1984.

This paper describes SesCon, a prototype expert system for advising a user of the SESAM - 69 structural analysis package on which method to use for a particular analysis. The decision is based on properties of the structure and the loads applied to it, as well as on analysis goals. SesCon was based on Emycin, an expert system package developed by Heuristic Programming Project at Stanford University (USA). The paper presents some background information to the development of SesCon Knowledge Base and gives an example of its use. Experience with SesCon is summarised and suggestions are made for possible extensions into other domains.

13. MacCallum, K.J., 'Creative Ship Design by Computer', Proceedings of Computer Applications in the Automation of Shipyard Operation and Ship Design IV, 1982.

Despite early indications of the potential of computers for aiding creative engineering design, only a few systems have been developed to assist in the process of design. It is the contention of this paper that current work on expert systems provides a key to realising the potential of Computer Aided Design (CAD). An experimental computer system which investigates the application of the expert systems approach to the creative stages of ship design is presented. The basic philosophy and key features of the system are described and, illustrated and evaluated for the example of a bulk carrier design.

14. Watanabe, O. and Iinume, M., 'Application of Artificial Intelligence to the Buckling Strength Design of Longitudinal Members of a Ship', Journal of Society of Naval Architects, Japan, 1988.

A prototype expert system for evaluating longitudinal strength design in bulk carriers is proposed in this paper. It was able to minimise routine work and also have a capability for efficient data control supporting reanalysis.

15. Petrov, P., Hadjimikhalev, V. and Haimov, A., 'A Knowledge-Based Propeller CAD System', Proceedings of Practical Design of Ships and Mobile Units, Newcastle, 1992.

This paper describes the methodology and the results of developing a knowledge-based system for screw propeller design, having new mechanisms for advice and expert knowledge support. The shell is based on OPS5-like language, having all the features of manipulating the knowledge and data base. It perform control functions in the integrated system giving control to different numerical and graphical CAD procedures. Several propeller design rules have been incorporated in the knowledge base. Some examples illustrating the performance of the system are presented. The system is regarded as user friendly for the designer and is open to further development.

16. Chou, Y.C. and Benjamin, C.O., 'An AI -Based Decision Support System for Naval Ship Design', Naval Engineers Journal, May 1992.

The decision support system (DSS) reported in this paper integrates conventional naval ship design application software and expert system. Modelling techniques such as spreadsheet, a database management system, and graphic display capability are incorporated as well. This DSS facilitates 'what if' analysis of design problems and assessment of the trade-offs between performance and cost. The DSS will aid rapid generation of design alternatives and facilitate their evaluation. During a structured system evaluation, the DSS displayed considerable accuracy, flexibility, speed, user-friendliness, and cost-effectiveness.

17. Sen, P. and Gerigk, M.K., 'Some Aspects of a Knowledge-Based Expert System for Preliminary Ship Subdivision Design for Safety', 5th International Symposium on the Practical Design of Ships and Mobile Units, Newcastle upon Tyne, 1992.

Traditional procedural approaches to computer aided ship design usually combine design knowledge and processing information in such a manner that incremental advances in design expertise are rather cumbersome to incorporate without extensive re-programming but his difficulty is more helpfully addressed in the knowledge based approach by an effective separation of logical processing elements from the knowledge. This is particularly helpful in the area of design of ships for safety because design knowledge in this domain is rather scarce and often becomes available experimentally. This paper deals with some aspects of the knowledge based design of passenger ferries with particular reference to subdivision using alternative probabilistic regulations, and arrives at some guide lines on the basis of a critical examination of the premises of the regulations. These rules are then applied to show how designs can be improved from the subdivision point of view.

18. Koyoma, T., Liu, J.P. and Yamato, H., 'Representation and Modification of Ship Hull Surface', Journal of Society of Naval Architects Japan, Vol. 166, Dec., 1989. (in Japanese)

In this paper, a method of representing a ship hull and a modification and fairing expert system are discussed. The hull is represented by a normalised B-spline surface. Instead of representing the entire hull by a single surface, it is divided into several parts which are represented separately. The B-spline surface is usually generated from points which consists of a mesh on the surface. An algorithm for generating the surface from the mesh curves is developed. With this, the waterline and station line can be used to generate the hull surface directly. For shape modification of the ship hull surface, an object oriented shape modification and fairing paradigm is proposed to overcome the difficulty of flexibility and consistency caused by the complexity of data structures and the relations between data. Based upon that paradigm, a test waterline and station line modification and fairing expert system was developed. Some results are given.

19. Calisal, S.M., Mikkelsen, J., McGreer, D., Akinturk, A., Havens, W. and Joseph, S., 'Fishing Vessel Design with a Constraint Reasoning System', Fourth International Conference on Computer Aided Design, Manufacture and Operation in the Marine and Offshore Industries, Spain, 1992.

An expert system which is based on a constraint reasoning system is developed to aid naval architects in the design of fishing vessels. The expert system incorporates knowledge bases derived from existing vessels series, government regulations, fishing vessel replacement rules, and classification society rules with design software such as resistance and stability algorithms. The systems also incorporates a new type of constraint logic programming system called Echidna. The Echidna concept permits the definition of constraints, tolerances, ranges and weight functions for vessel parameters such as length, beam, and hold volume. The system is suitable for preliminary vessel design since the built-in constraint processing easily facilitates the narrowing of parameters during each cycle of a design spiral. Preliminary estimates for resistance, stability, and weight groups are presented in this paper. A comparison between the new system with a previous expert system developed for use on the IBM PC is also given.