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THE APPLICATION OF
COSTING AND OPERATIONAL EFFECTIVENESS METHODS
FOR THE SELECTION OF HULL TYPES

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ANEP ON THE APPLICATION OF COSTING AND OPERATIONAL EFFECTIVENESS METHODS FOR THE SELECTION OF HULL TYPES

PREFACE

This Allied Naval Engineering Publication is intended to provide guidance to Naval Staff, Planners, Procurement Staff and Craft Designers on the consideration and use of costing and operational effectiveness **methods** for the selection of hull types for particular military roles.

It is divided into five sections

Main Document -	Outlines a proposed philosophy and its integration with the procurement process.
Annex 1	Describes and provides design information and performance prediction methods for the major classes of hull types.
Annex 2	Provides the results of a parametric study comparing three different hull types over a range of sizes and levels of performance.
Annex 3	Describes the methods and techniques used to assess craft design and estimate costs and the procedures used to implement cost and operational effectiveness analyses.
Annex 4	Application examples.

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LIST OF ABBREVIATIONS

ACV	Air Cushion Vehicle
AHP	Analytic Hierarchy Process
ANEP	Allied Naval Engineering Publication
ARM	Availability, Reliability and Maintainability
CBA	Cost Benefit Analysis
CDSP	Consensus Decision Support Programme
CER	Cost Estimating Relationship
COEA	Cost and Operational Effectiveness Analysis
COEIA	Combined Operational Effectiveness and Investment Appraisal
CORE	Controlled Requirements Expression
CPP	Controllable Pitch Propeller
EU	Expected Utility
EV	Expected Value
FPP	Fixed Pitch Propeller
FSH	Fully Submerged Hydrofoil
IDEF	Integrated Definition
IMOP	Interactive Multi Objective Programming
IR	Infra Red
IRR	Internal Rate of Return
LOA	Length Overall
LWL	Length on Water Line
MAUT	Multi-Attribute Utility Theory
MAVT	Multi-Attribute Value Theory
MOE	Measure Of Effectiveness ,
MOP	Measure Of Performance
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
NATO	North Atlantic Treaty Organisation
NPV	Net Present Value
PAPS	Phased Armaments Programming System
SES	Surface Effect Ship
SPH	Surface Piercing Hydrofoil
SWATH	Small Waterplane Area Twin Hull

LIST OF DEFINITIONS

Air Cushion Vehicle	A marine vehicle whose weight is wholly supported by a cushion of air generated by the vehicle and retained by a flexible skirt system attached to the vehicle itself.
Benefit	An attribute, quality, characteristic or measure of a system's performance that it is advantageous to maximise.
Catamaran	A multihull vessel with two hulls, usually symmetric about the craft's centre line.
COEA	Cost and Operational Effectiveness Analysis: The process by which cost/benefit analyses are performed and the results brought together to support procurement decisions. In the context of military systems the benefits are usually taken to be military effectiveness in defined scenarios.
Concept	The early phase of the procurement or design cycle, the aim of which is to investigate at high level a sufficiently wide range of possible solutions to an emerging requirement that the most cost effective solution will be included and can be identified. The output is a set of high level requirements together with possible material solutions defined at high level.
Constraint	A restraint or requirement specifying an attribute, quality, characteristic or performance parameter that must either be achieved as a minimum or not exceeded as a maximum.
Cost	Costs to be incurred and paid for by the Government, including both the Industry and Government effort. Can also be taken as a generic term to mean any quantity or measure which it is advantageous to minimise.
Cast-Effective	Term used to describe a solution that provides a reasonable balance between the effectiveness of a system and the cost of achieving it. In the context of military systems the major positive characteristic is its military or operational effectiveness while the negative is the financial and other costs of providing that capability. The process by which cost-effectiveness is assessed is the COEA.

Cost Estimating Relationship: An equation relating the cost of a work breakdown structure element to technical parameters characterising the element. These parameters may be physical or performance characteristics. CERs are generally derived from data taken from one or more existing vessels. They can then be used to predict the cost of a proposed similar vessel.

Design: The engineering process by which a material solution to a set of requirements and constraints is defined and optimised.

Development Cost: Cost required for research, development, test and evaluation of a programme. This includes costs for prototypes, instrumentation, project management, training, specialised support equipment, data, operational and site activation, tests and industrial facilities.

Diiunt Rate: The annual percentage rate at which the present value of a future investment or expenditure is estimated to decline as it is brought forward in time.

Disposal: Refers to the act of getting rid of excess, surplus, scrap or salvage property. This may be accomplished by, but not limited to, transfer, donation, sale, abandonment or destruction. When specifically applied to the final phases of a ship's life cycle, it entails the orderly processing of the ship for disposal which may include breaking up or sinking of the hull.

Feasibility Phase: The phase in the procurement process which aims to define the operational requirements for the ship, produce the basic parameters of a material solution and estimate its associated cost.

Function: An operation that is carried out by a system or sub-system.

Functional Analysis: The process of systematically identifying the functions carried out by a system and its constituent sub-systems.

Hull Form: The definition of a marine vehicle platform within a particular class or hull type. Defined by relative physical dimensions, shape parameters and geometric coefficients.

Hull Type: The generic class of a marine vehicle platform, eg. monohull, multihull, surface effect ship, etc.

Hybrid	A class of marine vehicle hull that when operating exhibits the characteristics of two or more hull types, eg. a catamaran partially supported by hydrofoils. Its distinguishing characteristic is that it is supported by at least two of the three types of lift, buoyant, powered static and powered dynamic lifts.
Hydrofoil	A marine vehicle where the vessel weight is wholly or partially supported by tbe dynamic lift generated by foii operating below the water surface.
Internal Rate of Return	The discount rate that would give a project a net present value of zero.
Life Cycle Cost	The total cost for a system or programme over its full life, including the costs of development, procurement, operation, support and disposal where applicable. It includes all cost elements incurred by the government and encompasses both the industrial and the government effort.
Measure Of Effectiveness	A measure of the benefit of a system defined in terms of the purposes for which the system is being acquired. For a military system the MOE would be appropriate to the strategic or tactical scenario within which the system is operating. The MOE measures the achievement of military objectives by the system. For example the measure of effectiveness for a mine clearance vessel would be the risk of damage to subsequent shipping using a cleared area.
Measure Of Performance	A metric describing the level of achievement of a functional characteristic, eg. speed, range, seakeeping, target engagement and destruction, etc. If a system is described in functional terms using a hierarchical breakdown then MOPs can be defined that are appropriate to each level of the hierarchy. Generally MOPs are specific to particular systems and MOEs can be used to compare competing systems.
Mission	An operation performed by a military system in pursuit of a defined objective. Typically a mission will be made up of a sequence of tasks.
Model	A mathematical, logical or numerical representation of a physical system and its operating environment that quantifies the measures of performance or effectiveness of the system.
Modelling	The process of describing, analysing and simulating in mathematical, logical or numerical terms the characteristics and performance of a physical system in a particular environment.

Monohull	A class of marine vehicle with a single hull supported by displacement or dynamic lift on that hull.
Multihull	A class of marine vehicle with two or more hulls. The hulls may be of different physical forms and or sizes.
Net Present Value	The capitalised value of a stream of future benefits and costs resulting from their being discounted to the present and summed.
Operational Effectiveness	The degree to which a system is able to achieve the military purpose for which it was designed.
Operational Evaluation	The process of assessing the military requirements and role of a system and identifying the measures of performance that contribute to success.
Operational Requirement	A statement of need for a new system preferably expressed in terms of functional performance related to military roles.
Operations and Support Cost	Costs associated with the operation and support of a ship after commissioning including those associated witb operating, modifying, maintaining, supplying and supporting a ship and its payload throughout the remainder of its life cycle including refit programmes and mid-life conversions, alterations and improvements.
Parametric Study	An investigation of a subject, design or process involving the systematic variation of the important contributory input data to ascertain their effects on the final outputs or results.
Partitioning Requirements	The allocation of functions to individual sub-systems or elements within a system.
Payload	The military sub-systems and components of a marine vehicle. Generally referred to as those elements that contribute to the “fight” function.
Performance	A measurement or description of the degree to which a functional characteristic of a system is accomplished.
Platform	The elements of a mark vehicle system that contribute to the “move” and ‘float” functions. The platform supports the payload and carries it wherever it is needed.
Point Design	A balanced and practical design generated to give a particular level of performance. It reveals tbe total-ship level characteristics required in order to provide that level of performance.

Programme Acquisition Cost
Consists of sailaway cost plus design and development cost, costs for training and support equipment, publications, technical data, operational and site activation, facility construction, initial spares and initial repair parts, national and NATO project management offices, contractor services (not already included in sailaway costs) and any other costs, prior to the in service phase, which are in direct support of the system or project.

Project Definition Phase
A phase in the procurement process designed to generate accurate knowledge of life cycle costs and sufficient data to allow a build contract to be let.

Risk
The combination of the likelihood (probability) of an event (usually, but not necessarily, an adverse event) occurring, and its impact. The impact may manifest itself in financial loss or gain, time delay or schedule improvement, reduction or increase in product performance and/or acceptability.

Role
A military function defined at thd strategic operational level. A role will be fulfilled by the execution of particular missions.

Sailaway Cost
Sailaway is used as a generic term related to the creation of a completed ship up to governmental acceptance. Sailaway cost includes
- Ship work breakdown elements such as basic structure, propulsion, electronics, etc., shipyard project management and system test and evaluation.
- All costs of the initial construction non-recurring and recurring cost categories, including allowances for changes, warranties, first destination transportation, etc.
- Allowances for excise duty, applicable sales taxes, freight and shipbuilder's overhead and profit.

It does not include one off costs such as design and development or the provision of support infrastructure, nor does it *cover operations* and support costs.

Scenario
The overall environment within which a function is carried out. This is generally, but not always, specified at high level and covers such factors as
- Political situation
- Force objectives
- Geographical/locations characteristics
- Natural environmental conditions
- Opposing forces

Simulation
A model of a system that characterises the functions to be performed by the system **and reflects the time based inter-relationships of those functions.**

Small Waterplane Area Twin Hull
A catamaran which has the supporting side hulls narrowed at the waterline in order to reduce the waterplane area at the design draft. The hulls are expanded below the waterline to produce the buoyancy to support the ship.

Standards
Mandatory performance or quality levels to be achieved. They may cover such areas as
- Design and construction rules
- Operating and manning philosophies
- support philosophies
- Standard materials and equipments

Sub-System
A component part of a system that performs a contributory function. Each subsystem may itself be considered as a complete system in its own right.

Surface Effect Ship
A marine vehicle whose weight is partially supported by a cushion of air retained by the immersed side hulls and a flexible skirt system fore and aft. The side hulls carry the remainder of the craft's weight.

System
A collection of functional entities or sub-systems interconnected so as to fulfil a logical purpose.

Task
A specific function carried out by a system pursuant to achieving an objective or mission.

Trimaran
A multihull vessel with three hulls. Usually a symmetric centre hull flanked by hvo smaller side hulls.

Uncertainty
The circumstance of not knowing exactly what will occur in the future or not being able to determine exactly the characteristics or performance of something.

Unconventional Hull Type
Any class or type of marine vehicle not of simple monohull form, or a monohull that has unusual characteristics.

1.0 INTRODUCTION

The ability to conduct military operations at sea has long been of paramount strategic importance for all maritime nations. Defence of trade and prevention of seaborne attack are vital roles. In addition the ability to conduct offensive operations widens political options and can act as deterrence in its own right. The fulfilment of these objectives in a wide range of operating conditions and threat scenarios results in the need for military craft with a wide range of characteristics. Some may need to fulfill several roles, others may need to be optimised for particular roles. In either case the demand to obtain value for money places ever- increasing pressure on the correct selection and design of naval combatants.

The marine environment will always place limits on the speed, manoeuvrability and seakindliness that can be achieved by any craft designed to operate within it. The design of military marine craft hull types has for long been dominated by the single hulled-displacement craft, or monohull, and this has reached a high state of development. It can be readily tailored to particular applications, for example the planing form where the craft weight is supported by dynamic lift in order to reduce high speed resistance. However, all designs involve a compromise, and there are inherent limits on the performance that can be achieved by a particular design concept.

It is in order to extend these limits in particular areas of performance that craft with unconventional hull types have evolved. The term unconventional hull type is here taken to mean any craft that is not of conventional monohull displacement or planing form. This includes craft such as hydrofoils where the hull is supported by under water foils, multihulls such as catamarans with two hulls or trimarans with three, Small Waterplane Area Twin Hull (SWATH) vessels, and craft wholly or partly supported by air pressure, such as Air Cushion Vehicles (ACVs) and Surface Effect Ships (SESs).

The need to obtain ever more value for money in all areas of defence procurement has led to the development of Cost and Operational Effectiveness Analysis as an essential element of the decision making process for all acquisition programs. The purpose of this document is to present sufficient data to allow the application of such cost and operational effectiveness methods to the initial selection of hull types for naval applications.

1.1 BACKGROUND

Over the last twenty years, the technology of unconventional craft has advanced to the stage where they can now be considered as viable alternatives to the more traditional monohull in many roles. However there has not proved to be a widespread adoption of such craft for military applications. In the past this has been due to uncertainties and risks in the technologies involved and, perhaps more significantly, a reluctance in some quarters to accept novel hull types in comparison to more conventional monohulls. There are several reasons for this, perhaps the main one being user conservatism.

In order to more fully explore the technologies and the military potential of unconventional craft, NATO established a Special Working Group, SWG 6, to investigate and report on the potential of such craft. Over the last few years an extensive programme of work has been performed involving parametric studies and the generation of point designs for several craft types for a variety of potential roles. (references 1, 2, 3, 4). In contrast, the commercial sector has seen a rapid expansion of the use of unconventional craft.

There are various reasons for this adoption of unconventional hull forms for commercial applications:

- Low Risk Technology
  The craft technologies are well known. Multihulls, surface effect ships and hydrofoils are all generally well understood technologies and are price competitive with monohulls in the higher ranges of presently achievable performance.

- **Performance Advantages**
  Most commercial applications of unconventional hull types have been in the fast ferry market. There are three major requirements for this application and although a particular hull type may not score highly on all three, the weightings on each requirement for a particular route often results in the selection of an unconventional craft. Tbe requirements are:
  - High speed and low delivered power
  - Large deck area in relation to payload weight
  - Good seakeeping

  The catamaran compares well with a monohull on the first two and can be satisfactory on the third witb appropriate ride control. Where even higher speeds and better motions are needed, the SES and hydrofoil become competitive. Both catamaran and SES allow more efficient layouts, with their large deck areas. A SWATH can provide excellent motions in all speed ranges but is relatively less efficient to drive at higher speed.

With the increasing pressure on defence budgets, there are two imperatives facing designers.

- Perform role **at lower cost**

- Perform more **roles with a single vehicle**

In the case of the first, the performance advantage inherent in an unconventional hull type may allow a cheaper unconventional craft to be as effective as a more expensive conventional one. In the case of the second, the unconventional hull type tuning for performance may offer both an advantage and a disadvantage. However, the more flexible layouts possible on the stable wide-beam craft are almost always advantageous.

In the past assessments of unconventional craft have been limited to technical comparisons and have therefore not allowed the potential of such craft to be fully and objectively explored. It is therefore necessary to be able to make a more objective assessment of the potential military uses of such craft from the earliest design phases, to ensure that the most cost-effective solution is selected. Such an approach was proposed in the final report of SWG6 (Reference 4).

This document has therefore been written to provide guidelines on the selection of hull types and hull forms for naval craft. The selection process described is applicable to all craft types both conventional monohulls and unconventional forms. In addition design guidance information is provided for the unconventional forms as this is less widely known in comparison to conventional monohull design practice. The studies performed under SWG6 concentrated on the generation of point designs and therefore only limited parametric investigations were performed. a **much** wider ranging **parametric** study covering three hull types is also provided.

1.2 OBJECTIVE

It is the objective of this document

- To assist **the rational selection of hull type and hull form (both conventional** and **unconventional) for particular military roles on the basis of cost and operational effectiveness.**

The information presented will allow a fuller assessment of alternative design solutions. At the early concept stages, the choice will essentially be between alternative hull types. As design work progresses, alternative hull form trade offs within the selected hull type may be performed using similar methods,

1.3 INTENDED USERS

The document is **designed to be** of assistance to

- **Operational Staff and Naval Planners**
- **Procurement Staff and Craft Designers**

The role of the former is to set the requirements to be met by a potential new class of vessel, while that of the latter is to satisfy them. It is well known that too early anticipation of the material solution to a particular high level requirement on the part of **either** group can prevent **the** consideration of potentially viable designs. This may be either by setting unnecessarily restrictive requirements or by inadequate consideration of alternative solutions. It is the purpose of this document to provide guidelines for both groups on how to avoid these **pitfalls** and to provide information on the methods and techniques to be used for hull type assessment and selection, together with design information on the unconventional hull types themselves.

1.4 STRUCTURE

The document describes the philosophy to be followed in order to ensure that appropriate consideration is given to all potential hull **type solutions to a military craft requirement.** The approach is based on considerations of cost and operational effectiveness.

It is supported by annexes giving more detailed explanations of craft types, design data, methods and procedure application examples. The annexes are

- Craft **Types and Design Guidance**
  Providing design information on alternative hull types.
- **Design Charts**
  Providing parametric data to **be** used in the initial selection and sizing of three alternatives hull types.
- **Analysis Methods**
  Providing a glossary and high level descriptions of appropriate analysis methods and tools and indicating how they can be applied to the assessment and selection of conventional **and** unconventional hull types.
- **Application Examples**
  The application of some of the methods described is provided using two examples.

2.0 PHILOSOPHY

It is essential that in order to evaluate properly the full potential of marine craft technology to fulfil a particular military role, the initial statement of need should not predefine the solution by specifying the type, size and performance to be provided.

2.1 FUNCTIONAL REQUIREMENTS

The requirements should be expressed in functional terms by describing what tasks should be achieved rather than how they are to be achieved. The requirements should therefore cover such issues as

- Operational scenarios
  These cover the political and military possibilities envisioned by high level political direction and naval planners.

- Roles to be fulfilled
  Describing the high level military functions to be carried out.

- Areas and environments of operation
  As a consequence of the above requirements the particular conditions and threats that are likely to be faced will be defined.

- Levels of performance
  This should not be too detailed but in addition to operational performance should address such issues as availabiity and support considerations and also any operational interfaces such as with shipborne aircraft.

The requirements will also lay down the constraints to be observed. These may include many factors but typically cover such issues as

- Budgets

- Standards
  Here standards are used in the widest sense and encompass
  - Statutory design and construction rules, guidelines and policies
    These will address safety considerations and performance thresholds for particular items.
  - Operating and manning philosophies
  - support philosophies
  - Standard materials and equipments

- **Uncertainties**
  The data and information on which the different phases of the acquisition process depend will always be subject to uncertainty. As far as possible this must be quantified and contingencies provided. A typical example is the provision of margins during the design process.

- Risk
  The level of risk that may be acceptable will depend upon
  - Availability of competing programmes
  - Penalty for failure to meet requirement
  - Requirement for capability advantage

2.2 ASSESSMENT

These requirements and constraints thus determine the basis of any assessments and subsequent selection carried out during the procurement or acquisition process.

The assessment task is then concerned with determining how well a proposed design meets the requirements and constraints laid upon it. Various factors must be addressed and these fill under the six broad headings of

- **Technical**
  How well the design standards are met. This includes consideration of cases where there may be benefit in exceeding them.

- **Operational** Effectiveness
  How well the functional requirements derived from the military mission are met.

- **Cost**
  Budgets, both acquisition and through-life.

- **Timescale or Schedule**
  Development, design, build and trial programmes.

- **Uncertainty**
  The information on which the assessment is based is subject to uncertainty. This applies both to knowledge of the system itself and to data on the scenarios against which it is being assessed.

- Risk
  Classified under the headings of Performance, Cost and Timescale or Schedule. Performance is here taken to include all technical risk issues.

These headings are common to all design assessments but become more complex when unconventional craft are compared with traditional monohull designs. Particular problems are likely to occur in the areas of technical and cost assessment. There are two main reasons for this

- **Comparative lack of past design data**

- **Difficulties in comparison of designs** of different generic types

The first problem is diminishing in significance as more design investigations are performed and more unconventional craft are produced and enter into service. However, many of these craft are built to commercial standards and the effects of imposing military specifications will need careful consideration. The second problem is more intractable. The whole reason for the development of unconventional craft is that they offer performance advantages over more conventional designs in particular areas, for example speed or seakeeping. In addition, their operating characteristics may result :in different manning requirements. However, performance advantages in one area are often obtained either at the expense of performance in another area or an overall increase in cost or time schedule. There is thus a need for an assessment mechanism that recognises the impact of different levels of performance of relevant characteristics on the overall objective. Detailed technical assessments alone will tend to concentrate on how well the particular design performs as a representative of its generic type, whether this be monohull or any other class of vessel.

The objectives against which the options are assessed must be defined in the requirements in a manner that does not predetermine the solution. It is then possible to bring together the satisfaction of various requirements and constraints to determine the overall **Cost-Effectiveness. In this** context this is defined as the balance between benefits, which are attributes that need to be maximised, and the costs of achieving those benefits.

An important point to remember is that measures of benefit must be considered in the widest possible context. A naval craft is part of a military system, and it is the objectives of this whole system that must be examined. Each element of a system can affect the performance of another element and so all should be considered when evaluating one. As an example, platform signature characteristics and electronic counter measures systems performance are intimately related. If too narrow a view is taken then the traditional problems of restricting potential solutions will occur and opportunities will be missed.

The benefit in this context means the military effectiveness or the degree of success in the fulfilment of **the military role** or mission. Effectiveness is quantified **by Measures Of Effectiveness** (MOE). Mission success will be dependent upon numerous contributory factors each of which can be determined by more detailed assessment. The contributions of the individual factors to the overall objective are generally characterised by a high degree of interdependence among them. If measures of overall operational effectiveness are then used as the basis for assessment the comparison of solutions that offer widely different performance levels in different areas becomes much easier. The individual **Measures of Performance (MOP)** are not then considered in isolation but only as contributing factors towards the measures of effectiveness or military benefit.

The other side of the costeffectiveness equation will include such factors as cost, timescale or schedule, uncertainty and risk. Just as technical assessments feed data into effectiveness studies, so they will also feed into assessments of design risk and cost estimation procedures.

The six different areas of assessment listed above are therefore closely related and mutually dependent. However it is necessary to combine them together in a manner that displays the overall cost-effectiveness of the competing options. This implies that a range of measures representing completely different quantities must be brought together in a rational manner. This problem is made more difficult by the fact that there are often additional factors which are relevant to the cost-effectiveness equation but which are not so easily quantifiable and in fact can often only be asses& using subjective judgement. However there are methods available that can substantially overcome these difficulties, and they form the final stage of the assessment process.

2.3 COST AND OPERATIONAL EFFECTIVENESS ANALYSIS

The philosophy that addresses **these** issues is **known** generically **as Cost and Operational Effectiveness Analysis** (COEA). There may be national variations; for example, the approach is **termed Combined Operational Effectiveness and Investment Appraisal (COEIA)** in the United Kingdom.

Application of the philosophy is not as straightforward as a conventional technical assessment but is necessary if dissimilar system solutions are to be compared (references 5, 6).

It is of course important that the assessment process must be both visible and auditable and so the approach can be broken down **into several stages.**

2.3.1 Determination of Operational Requirements

In general the generation and finalising of requirements is an iterative process linked to the generation and assessment of design solutions. The aim of the iterations is to ensure that the requirements are realistic and can be met within cost and timescale or schedule budgets with an acceptable level of risk, all relevant factors being known with a sufficient degree of certainty.

It is essential that definition of operational requirements is maintained at a functional level and does not define the material solution. There may be obvious constraints to be defined, such as compatibility issues, but even so these must not be too restrictive unless the implications are fully understood both in the wider scale and for the particular proposed role.

The development and production of the requirements themselves is a multi-level activity where each element operates within a framework and constraints set by the previous level. This is illustrated in an idealised form in figure 1. All levels may not necessarily be involved in any particular procurement programme.

Organisation	output	Constraints	Requirements
Government	Objectives	Budgets/timescales Policies Legal	
Force command	Context	Doctrine Support & logistics Interoperability Compatibility	
Naval planners & analysts	Scenarios Robs & Missions		Environments Threats Assets
	Required measures of effectiveness		Functional requirements
Procurement staff	Sub system specifications	Budgets Standards	Performance targets
Craft designers	Designs		

Iteration

Figure 1: Derivation of Requirements

A small project may only need the involvement of the lower levels in the hierarchy. The major generic elements in the requirement derivation process an:

- **Government**
  The Government will set the strategic objectives of the forces.
  They are also responsible for setting various guidelines and constraints covering such issues as
  - Budgets
  - Policies
  - Timescales
  - Legal factors

  They will also have to balance one programme with another, which may result in yet further pressure on the constraints.

- **Force Command**
  The context within which the requirements will be progressed will be set. This can be manifested as constraints brought about by the existing structure, organisation of the force and other programmes and will involve such issues as
  - Doctrine
  - Support
  - Logistics
  - Interoperability
  - Compatibility

- Naval **Planners and Analysts**
  The objectives will be interpreted and developed into a variety of high level scenarios. From these will flow definitions of the following
  - Operating environments
  - Threats
  - Assets

  The planners are also responsible for the definition of the roles and missions to be performed by the new system. The naval analysts will be responsible for devising the measures of effectiveness for assessing possible solutions to the requirement. It is important that these measures of effectiveness consider the wider system implications affecting likely new equipments. In other words they should be defined in the context within which the new equipment operates rather than the measures of performance of the equipment itself. The analysts will also expand and develop the functional requirements of the new system.

- **Procurement** Staff
  Responsible for satisfying the requirements set by the previous authorities. There is a large degree of overlap with the craft designers as there must be an understanding of what is practical in order to develop subsystem specifications. The staff who develop design solutions are in the best position to partition the requirements. Partitioning involves the allocation of system- level functional requirements to particular sub-system elements. If the requirements are specified at a system-level then the requirements of a naval craft to operate as part of that system will be defined in parallel with craft design studies. Requirement partitioning will also particularly affect the combat system payload components of a naval ship. The procurement staff will also be responsible for defining the standards to be met by any practical equipment solutions and they must judge the acceptability of the risks inherent in each alternative design concept and assess the feasibility of developing the design within the imposed budget and programme constraints.

- **Craft Designers**
  Craft designers will work in parallel with the procurement staff in developing the final requirements by developing alternative possible solutions to ensure that the final requirements are achievable and that potential solutions are offered that can be demonstrated to be cost effective.

Although these elements are shown as following one another in a step by step sequence, there is an inevitable degree of iteration as work at one level will raise issues which prompt a reexamination of the assumptions already made at a higher level, leading to a repeat pass through the system. The process itself can become a little blurred in day-to-day operation, as continuous two way communication occurs, but it is generally controlled by the necessity of obtaining approval at each procurement phase for policy statements, procurement strategies, requirement statements, tender documentation, etc.

2.3.2 Definition of Systems

The freedom which designers have will depend on the degree to which the requirements do not go beyond specifying functionality and start to dictate the solution. It has already been stressed that the requirements definition and the complementary fulfilment processes are strongly interdependent, and therefore iteration is always necessary.

Ideally the designers will be allowed maximum freedom during the early iterations of the requirements specification/fulfilment cycle in order to ensure the maximum opportunities to exploit potential solutions. This should allow alternative system designs to be developed and analysed. The term system here implies more than just the platform and its on-board weapon systems. It is taken to include all the equipments and processes involved in the fulfilment of the prescribed roles or missions. A design policy should actively encourage alternative approaches to the mission to be postulated, which will in turn encourage different platforms and equipments to be fully considered.

A single pass top-down flow from requirements setting to sub system design is illustrated in figure 2.

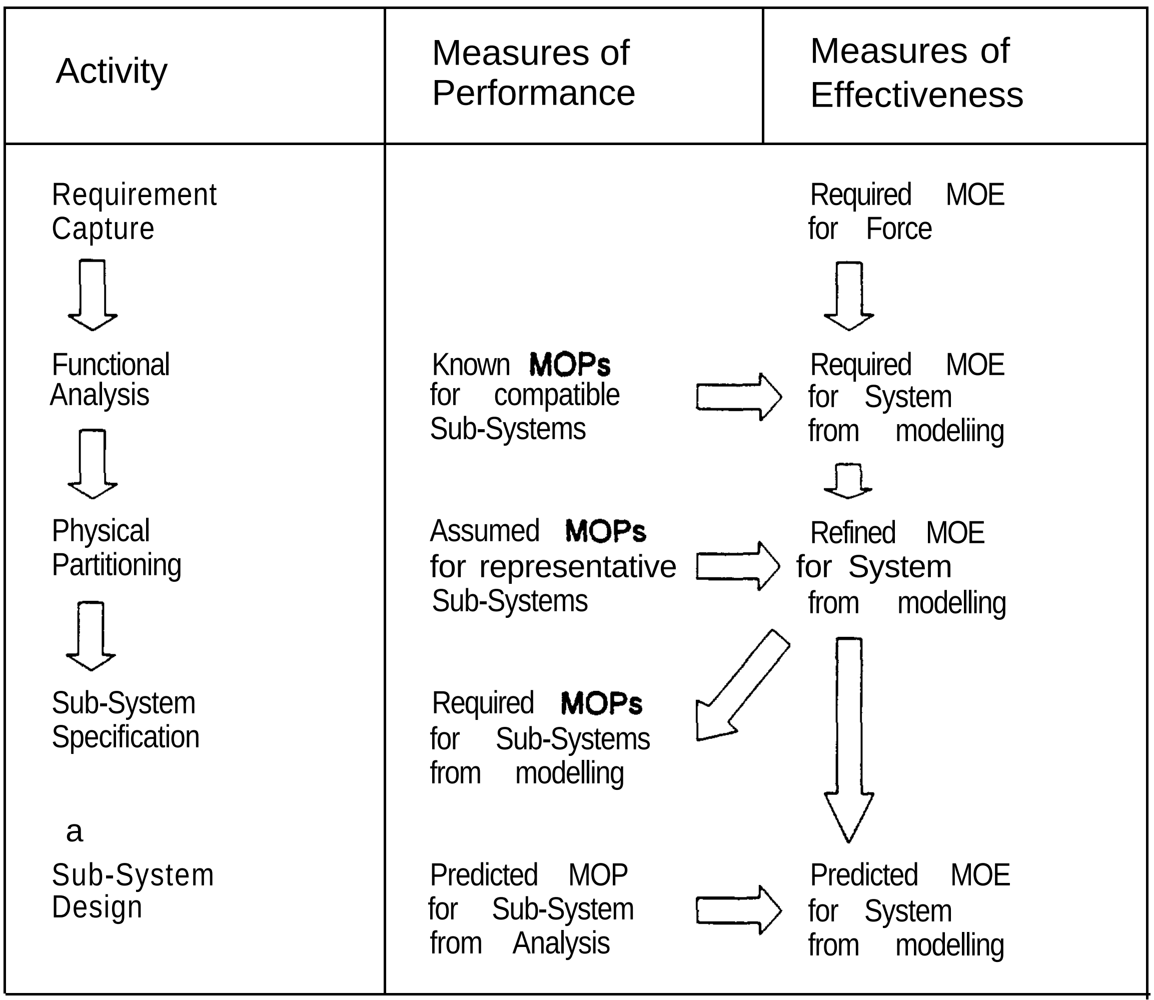

Figure 2: System Design Process

The major elements of this process together with the appropriate applications of performance modelling are as follows

- **Requirements** Capture
  This has been addressed in general terms in the previous section, but it is necessary to go down to a low **enough** level of detail to ensure that all the constraints are identified and defined sufficiently for their implications to he properly considered.
  High level, i.e. at force level, MOEs can be postulated at this stage.

- **Functional Analysis**
  'Ibis stage structures the requirements and identifies the processes involved in satisfying them. This is the first stage of system design but is limited to the functional level only, i.e. the what rather than the how.
  An MOE for the new system under consideration can now he derived from force level modelling knowing the contributing MOPs from other sub-systems within the force.

- **Physical Partitioning**
  Once the functional analysis of the requirements has been developed, the constituent functions or tasks must he partitioned in or&r to allocate them to particular physical sub-systems. The partitioning needs to be done with knowledge of the practical engineering constraints on the likely sub-systems. A large system may be partitioned in different ways depending on the performance characteristics of alternative physical sub-systems. This is particularly important for naval hull type selection, as different hull types are optimised for different measures of performance. As an example, craft with high dash speed potential working in conjunction with offboard surveillance systems may be an alternative to a larger slower craft with its own onboard surveillance system for use in an offshore patrol role. The partitioning of the sub-systems is thus a very important consideration in the selection of alternative hull types.
  A partition is often established between platform and payload for a warship. This is a somewhat artificial and simplistic split which neglects the critical performance interdependence between hull features and systems and weapon or sensor systems. The term payload is used in this document for convenience to refer to weapon and sensor equipments that are then fitted to a hull in order to make-up functional sub-systems and systems.
  The likely MOPs for each possible sub-system can be used to support the prediction of the system MOEs through modelling techniques.

- **Sub-System Specification**
  The requirements of the various elements of the system can now be defined.

- **Sub-System Design**
  Once the various elements have been identified, detailed design can be carried out. An indicative craft design process based on the use of databases is shown in figure 3.

ln practice it is generally useful to perform parallel bottom-up studies in which typically, baseline **designs** are taken or generated and modified to meet the emerging requirements. The value of such activities is that practical engineering constraints can be identified early on and fed into the overall top-down process providing a useful check on the realism of the outputs.

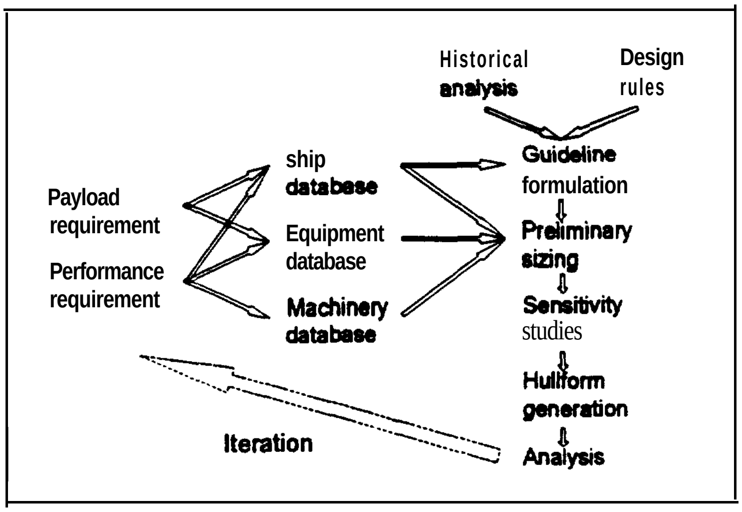

Figure 3: Indicative Craft Design Process

2.3.3 Analysis of Costs and Benefits

Traditionally a cost-benefit analysis has both costs **and** benefits expressed in the same financial terms. **However,** for a COEA both terms are used in a more **general** sense. In this context cost is taken as any undesirable parameter and **benefit** is generally defined by one or more **MOEs.**

The outputs from the requirements development stage outlined in the previous section **establish** a framework for analysis of possible solutions. Each level of requirements definition has a corresponding level of analysis in which the performance or compliance of candidate solutions are assessed against the requirements. The analysis process can be considered as a matching bottom-up approach to the top-down requirements setting process where the requirement levels and the appropriate analyses are as shown in figure 4 and described as follows:

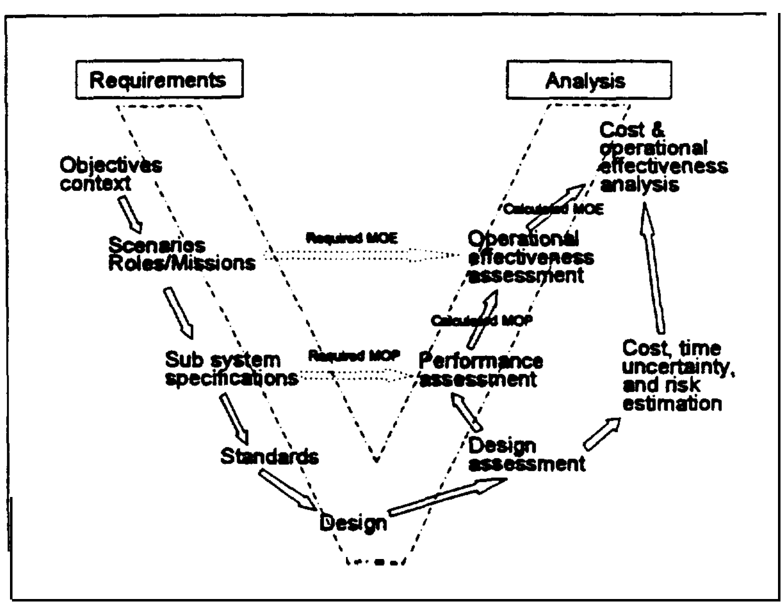

Figure 4: System Requirements and Analysis

- **standards**
  Candidate solutions are assessed for compliance against specified design standards during a **Design Assessment** process.

- **Sub-System Specification**
  The specifications will call for particular levels of performance under various headings. **Actual performance** will be determined by **Performance Assessment** and analysis. In parallel **Cost, Time, Uncertainty and Risk Estimation** will be performed.

- **Scenarios, Roles, Missions and Measures of Effectiveness**
  Operational Effectiveness Assessment employs a range of techniques and methods to evaluate military system designs in operational environments. It quantifies the MOEs specified as criteria for assessment in the requirements analysis stage (reference 7).

- **Objectives and Context**
  Once data is available from tbe operational effectiveness analyses and the cost, timescale, uncertainty and risk estimation procedures there will still be other factors to be taken into consideration. These may be both quantitative and qualitative and could include such factors as political considerations. All these factors contribute to the decisions made as a result of the overall Cost **and Operational Effectiveness Analysis.**

When applying this framework to a particular project it is useful to prepare a **Concept of Analysis. This** describes the detailed application of the process and will include:

- Options
- **Data available and any assumptions**
- **Operational scenarios**
- **Measures of effectiveness**
- **Operational** effectiveness **methods**
- **Costing methods**
- **Risks and uncertainty**
- **Other factors to be considered**
- **Selection methods**

2.3.4 Selection of Most-Cost-Effective System Concept

In order to reach a decision as to which design or option to procure, all the information generated in the analysis process must be brought together in a logical manner. The range of **information** is likely to include

- **Costs**
  Life cycle cost
  - **Program** acquisition cost
    - Design and development
    - Technical data and publications
    - Support and training equipment
    - Initial spares
  - **Facility** construction
    - **Project** lead ship cost overhead
    - **NATO** and national project management offices

- Sailaway wst
  - Project management
  - Hardware
  - Software
  - startup
  - Allowance for changes
  - Test and trials
  - Initial outfit
- operations support
  - Personnel
  - Consumables
  - Direct maintenance
  - Sustaining investment
  - Other direct costs
    - Engineering and technical services
    - Documentation updates
    - Training and simulators
    - Fees and rents
    - Helicopter operation
    - Handling of government owned stores
- Indirect costs
  - Personnel acquisition
  - Test and training sites
  - Support personnel and installations
  - Navy command
  - Transportation and logistic supplies
- Load-out items
- Disposal

- **Benefits**

  Operational effectiveness made up from one or more MOE.

- **Other**

  These can be considered as either costs, benefits or qualifiers on other data
  - Timescales or schedules
  - Uncertainty
  - Risk
  - Political factors
  - Employment considerations
  - International collaboration
  - Legal conventions
  - Industrialbase

Benefit measures are generally expressed in terms of one or more MOEs. It is desirable to keep the MOEs at a high level so that they capture as many differentiators as possible. However, it is inevitable that the consideration of alternative roles will result in an increase in the number of MOE figures that have to be considered during the final analysis. Similarly the presence of the additional factors indicated above will require the use of an analysis approach that allows the incorporation of expert judgement in order to obtain a fully considered, consistent and auditable conclusion. Therefore it is essential that subjective judgements as well as quantitative analyses are taken into consideration. Finally uncertainties in the analysis assumptions and data itself will require sensitivity analyses to be performed in order to ascertain their significance.

There are many techniques available to perform such an aggregation process all having the broad aim of combining disparate quantities or measures into overall estimates of cost and benefit. Although in theory everything can be distilled down to a single figure, this is not usually desirable as it is generally more useful to separate costs from benefits. In this way the amount of a particular benefit or cost can still be seen and this could allow different procurement programs to be balanced against each other.

In this context the term 'benefit" is taken to be the aggregate of all advantageous measures, generally MOEs. Methods that allow decision makers to perform this aggregation process over apparently widely differing measures are described in Annex 3.

The process is perhaps best considered as a means of showing how well particular options provide value for money at their own cost level. This is illustrated in figure 5. In this way an idea of the optimum cost-benefit curve can be obtained and a decision made as to what level of benefit is worth paying for. In this context the term optimum refers to the Pareto optimum, where the optimum curve is defined by options that provide the maximum possible benefit for a particular cost level or conversely provide a defined level of benefit at the cheapest possible cost. It is quite possible that constraints on costs or specified minimum levels of performance may dictate the final solution.

However if the cost and benefit identification process is performed during the early iterations of the requirement setting/design cycle then the budgets, constraints and requirements, where operational considerations allow, can be tailored to ensure tbat the ultimate solution lies on the Pareto optimum curve, i.e. is as cost-effective as possible. This may be at a point where the rate of increase of benefit with increasing cost starts to fill off more rapidly and it becomes uneconomic to pay for any further increase in benefit.

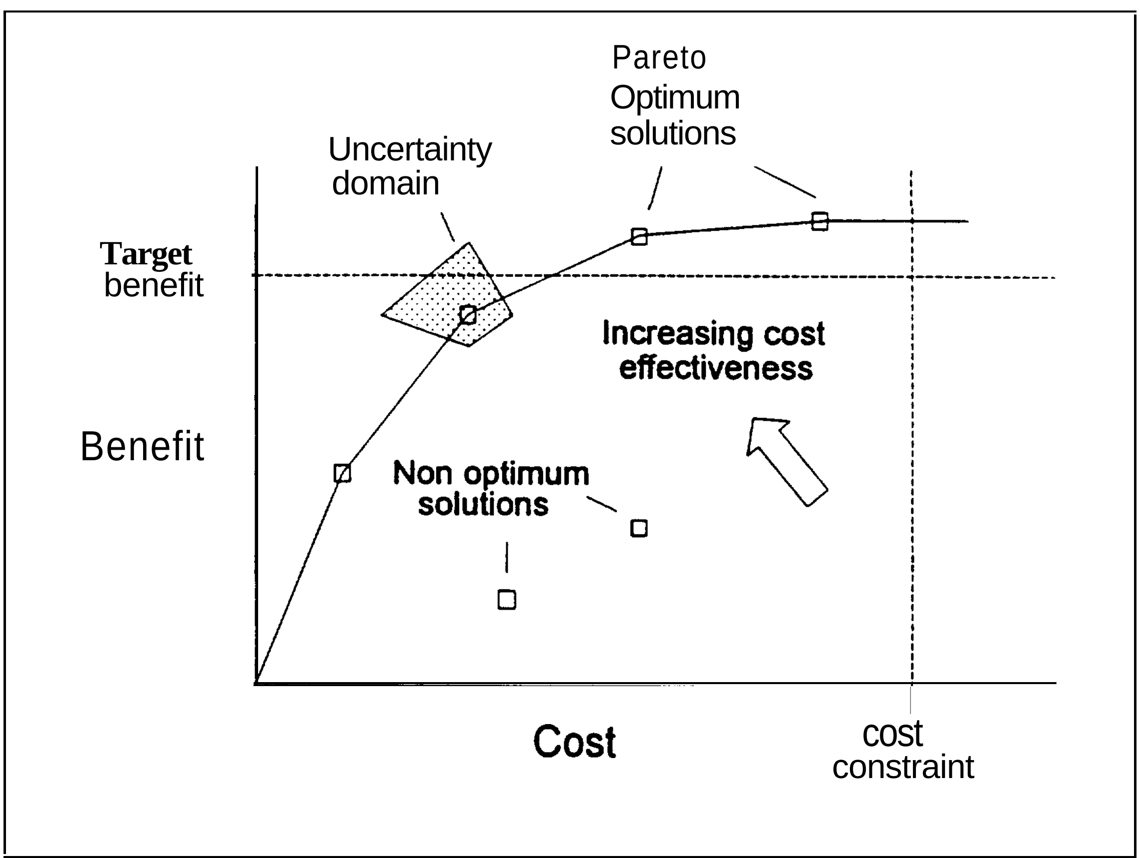

Figure 5: Cost-Benefit Trade Off

An important point to note in any of these processes is that the aim is to make a selection between feasible discrete solutions. It is therefore lmportant that sensitivity analyses are conducted at every stage for two reasons

- **Ensure optimum solutions are found**
  Any opportunity to improve the cost-effectiveness of a solution should be taken. If it can be shown that changes have a beneficial effect on cost or effectiveness without adversely affecting the other, then making the changes will make the solution more cost-effective. This is one reason why the assessment process should be closely integrated with design.

- **Ensure discriminators are identified**
  Factors that discriminate between solutions must be identified. Sensitivity analyses should be undertaken to ensure that apparent differences between options are outside the accuracy tolerances of the methods used. In other words the differences between the options are real and have not resulted because of the choice of particular analysis or assessment methods. In addition the effect of any uncertainties and consequent assumptions should be examined to establish their influence on and risk to the final decision.

The effect of these uncertainties can be shown on the cost-benefit plot. Rather than showing each option as a single point, it becomes a region bounded by the limits of the uncertainty in one or both of benefit and cost. This domain actually represents a probability distribution defined by the probability density functions of the two parameters. If the domains of two options overlap, then the probability of the options' ranking changing can, in theory, be calculated.

Once the curve of optimum solutions is defined, a final selection can be made.

The final selection may be made on the basis of a range of different criteria (reference 8).

- **Constant Cost**
  Select the option offering the highest benefit for a given cost.

- **Constant Benefit**
  Select the cheapest for a given level of benefit. These two criteria require that adjustments are made to the options to bring them to the same level of cost or benefit. This may not be possible in which case other criteria are possible.

- **Cheapest Compliant**
  A benefit threshold provides a constraint for selection of the cheapest.

- **Most Cast-Effective**
  The option with the highest benefit/cost ratio. If all options are on the Pareto optimum curve, this would usually mean the cheapest option with least benefit. In reality many options will be beneath the curve.

- **Aspiration Level**
  The option which maximises benefit or minimises cost across all scenarios (very similar to the simple threshold constraint criterion).

- **Most-Probable Future**
  The option which maximises benefit or minimises cost in the most-probable scenario.

- **Expected Value**
  The option which maximises benefit or minimises cost over all scenarios after weighting.

- **Laplace**
  The option which maximises benefit across all scenarios weighted equally.

There are also a range of more general criteria derived from decision analysis theory.

- **Maximin**
  The option which has the highest benefit in the worst-case scenario.

- **Maximax**
  The option which has the highest benefit in the best-case scenario.

- **Minimax Regret**
  The option which has the least reduction in benefit from the best alternative in any particular scenario, whatever scenario is considered.

It is quite possible that the costs and benefits obtainable within one project may have to be balanced against those obtained from a whole range of others. The final decision will therefore be influenced by a wider cost- effectiveness study which will set the constraints and budgets for the constituent projects.

It is therefore very important that the boundaries of a particular project COEA are clearly defined and all analyses performed within those boundaries.

Finally it is vital that any process is understandable, documented and auditable.

3.0 PROCUREMENT PROCESS

No assessment method can be considered in isolation from the overall procurement process of which it is a part. Therefore it is necessary to define a representative product life cycle incorporating development, acquisition and support within which the proposed method can be operated.

Such a cycle will have as its objectives the implementation of the tasks outlined in the previous section and their continuation into the production and through-life support of the resulting vessel. The tasks will therefore include

- **Determination of operational requirements**
- **Definition of potential design solutions**
- **Analysis of costs and benefits**
- **Selection of preferred solution**
- **Development and detailed design**
  Realisation of the selected option.
- **Production**
  Including construction, delivery, trials and acceptance.
- **Through-life support**
  Including refits, updates and eventual disposal.

It is important and in fact inevitable that the early phases of product procurement are iterative. initially they will concentrate on matching the generation of requirements to the development of solutions. These two activities progress together as requirements are modified in the light of knowledge of the cost of achieving them. The overall aim is to ensure that the final agreed requirements will lead to the production of a solution that is both technically achievable and affordable and is also the most cost-effective possible. This iterative process is in fact relevant to several different phases of a product's life cycle, and so its practical application will be considered in the context of each phase.

There are many definitions of such a product life cycle in existence but all have a broadly similar structure. In all cases the early phases are aimed at capturing the requirements and developing an appropriate procurement strategy while the later phases concentrate on risk reduction. A typical cycle is shown in figure 6 . This is taken from the NATO Phased Armaments Programming System (PAPS) (reference 9) and is representative of the cycle used by many nations. This cycle comprises the following major phases

- **Mission Need Evaluation**
- **Pre-Feasibility**
- **Feasibility**
- **Project Definition**
- **Design and Development**
- **Production**
- **In Service**
- **Disposal**

All the phases will not always be required for any given procurement programme. The distinct phases as shown are also liable to be influenced by other factors

- **Changing Relationships Between Government and Industry**
  As procurement policies evolve and with the changing role of prime contractors with regard to risk so the programme phases will change. Once a contractor takes on **responsibility** there is likely to be less scope for changes and development as costs would otherwise rise.

- **Concurrent Engineering**
  'he trend to parallel design and production engineering activities will blur the distinction between phases.

Phase	output	Approval
Mission Evaluation	Functional Requirement	Outline Staff Target
a Prefeasibility	Possible Solutions	Staff Target
Feasibility	Practical Design/s	Staff Requirement
Project Definition	Technical & Programme Definition	Design Objective
Design & Development	Detail Production Design	Production Objective
Production	Completed Vessel	In Service Goal
In Service	Updated Vessel	
Disposal	Removal From Service	

Figure 6: Product Life Cycle

The examination of **alternative** design solutions will be concentrated in the Pre-Feasibility or Concept phase. It is generally during this phase that the comparisons between competing unconventional hull type and conventional **monohull** designs will be performed. However, with the trend towards more open **procurement** the **process** may be repeated at later tender phases, particularly if a potential supplier wishes to **offer** an alternative system solution and the requirements are still open enough to allow this. The **cost**-effectiveness analysis process is of course applicable **at a** lower sub-system level, both during early development phases and during refits or update programs.

The phases are described more fully in the following sections.

3.1 MISSION NEED EVALUATION

This phase is performed in order to establish an Outline Staff Target. It will contain the broad functional requirements together with preliminary cost and timescale estimates. The aim of the phase is thus to reach general agreement between all interested organisations on the high level requirements and budgets.

3.2 PRE-FEASIBILITY PHASE

The output from this phase is a staff target refining the requirements and budgets proposed in the Mission Need Evaluation phase. Work will also be performed in order to define a range of possible practical technical solutions.

This phase is the most important from the point of view of selection of hull types. It can be divided into three sub-phases conveniently defined as:

3.2.1 Concept Exploration

During this sub-phase a number of different options are examined. Studies will focus particularly on developing operational requirements and sometimes philosophies and will investigate the interaction of the proposed roles/missions with other associated roles and their practical fulfilment. The term "whole system" is often applied to such investigations.

3.2.2 Concept Studies

This sub-phase will involve the exploration of particular solutions to the refined requirements developed in the Concept Exploration stage. Widely different designs may be considered. This is the sub-phase in which the possible adoption of unconventional craft solutions needs very careful investigation and assessment. Unconventional hull types are likely to require more design effort during this preliminary sizing activity due to the relative lack of design data. Most unconventional craft design data is from commercial projects and has limited applicability to military craft. The production of several preliminary point designs may be required in order to ensure a comparable risk level to a conventional monohull design sized on the basis of past data.

3.2.3 Concept Design

This final sub-phase in the Pre-Feasibility phase concentrates on developing several promising solutions to an outline design state. Proposals will be sized and their major measures of performance determined. A sketch layout will also be produced. At the end of this sub-phase the most promising designs, at least two and possibly more, will be selected for further investigation.

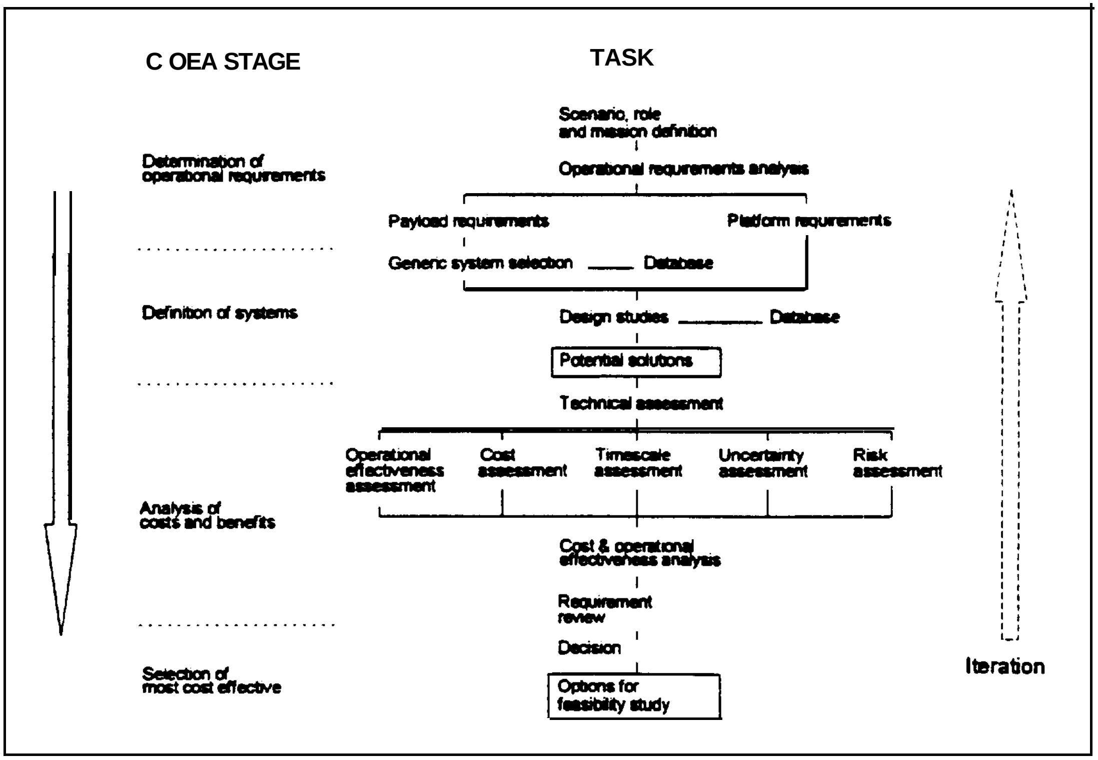

Figure 7: Typical Pre-Feasibility Phase

The various tasks performed in the **Pre-Feasibility** phase are illustrated in figure 7. The tasks are somewhat idealised and of necessity will be iterative in nature. They implement the activities described in the previous section. The three **sub-phases** essentially follow the same pattern of activity although the emphasis and level of detail covered will vary. During the concept exploration phase designers will concentrate on the early activities and will use very high level design tools in order to provide input to the operational requirement analysis iterations. The remaining two sub-phases, Concept Studies and Design, can be considered as successive iterations through the design study and assessment cycles, the later loops considering fewer options but in more detail.

The activities involved to varying degrees in each sub phase are

- **Scenario, role and mission definition**
  Any military requirement is based on countering perceived threats within a given operational **scenario. These must be identified** and potential means of countering them **formulated. As** a result of **such investigations, a preliminary** role definition will evolve.

- **Operational requirements analysis**
  The purpose of this activity is to develop the role definition and identify the key measures of **effectiveness** that contribute to success. Different mission profiles may be postulated **requiring** different solution characteristics.

- **Payload requirement defiition**
  Once the roles and possible missions have been defined, a set of draft requirements for weapon performance can be specified.

- Generic system **selection**
  Payload selection will **be performed** on the basis of performance and cost- effectiveness. During the Concept phase, the systems will be non-specific.

- Equipment database
  This database contains information on representative payload equipments suitable for inclusion in a concept design package. Typical data will include:
  - Functional performance
  - Availability, reliability and **maintainability**
  - Manning and workload implications
  - Weight
  - Space
  - Power Requirements
  - Cooling Load

- Platform requirement **definition**
  The platform performance requirements can be specified similarly.

- **Design studies**
  This task will **generate** a range of possible solutions to the requirements, generally using computer design synthesis tools. As wide a range as possible should be considered, covering not only differing system **configurations** but also alternative mission profiles where appropriate and practical.

- **Concept database**
  This database contains the data required to produce a balanced outline design for particular hull types. Its exact contents will depend on the sophistication of the concept design tools available but **will** generally contain:
  - Weight, space and performance data of previous designs
  - Design rules developed from past data
  - Design rules generated from first principles
  - Major equipment data such as for main engines, generators and weapon systems

- **Technical assessment**
  The design is examined and reviewed to ensure:
  - Technical feasibility with available or anticipated technology
  - Adherence to appropriate standards

  In addition, performance predictions will he performed to provide such data as:
  - Speeds, ranges, seakeeping and survivability
  - Threat detection, engagement, kill or avoidance

  if these are **not** produced directly by the concept design tools.

- operational effectiveness **assessment**
  The measures of effectiveness identified in the earlier operational evaluation **task** will now be derived for the competing design solutions.

- cost estimation
  Cost estimates will cover not only those **costs** incurred during development and acquisition but, as far as **possible,** the costs of operating and maintaining the vessels. There will of course be a large interdependence with **timescale** or schedule and programme assessment.

- **Timescale or schedule assessment**
  The programmes and times required to realise the potential designs will have to be estimated.

- **Uncertainty assessment**
  All data is subject to a degree of uncertainty, and this needs to be quantified through analysis of the assumptions behind the data. The sensitivity of the results to realistic variations in data values must be examined.

- **Risk assessment**
  This task will assess the risks of the design in technical, financial and programme terms.

- **Cost-effectiveness assessment**
  The results of the assessments produced above will need to be combined into an overall cost/benefit analysis. This will indicate the likely near optimum solutions that will then be worth progressing to feasibility studies. Alternatively it may indicate how a particular design concept would need to be changed in order to make it a realistic solution lying on the Pareto optimum curve, which would require an iteration of the process.

- **Requirements review**
  The information gained so far may indicate that either the mission requirements were too onerous or perhaps that there are better alternative ways of fulfilling the required roles. Either way, review may lead to another iteration of the process.

- **Decision**
  Once assessments have been performed on the competing options, a decision will be made as to which of the more promising solutions are to be taken to the more detailed Feasibility phase.

3.3 FEASIBILITY PHASE

The major purpose of the Feasibility design phase is to ensure that the requirements are reasonable and that the outline designs selected from those produced during the Concept Design sub-phase can be developed to a practical solution without too much risk. The design or perhaps designs will have been investigated and defined in some detail. If the risk to performance, cost and timescale turn out to be too high then the original requirements will need to be changed. In this way the Feasibility phase is used to finalise the requirements. In addition, the preferred final solution will have been identified and the likely costs estimated. The formal output from the phase will be an agreed Staff Requirement and a plan for the fulfilment of the project that includes the procurement strategy.

It is important that the requirements are expressed in terms which can be measured during eventual acceptance of the system. The acceptance strategy and criteria must therefore be developed alongside the requirements themselves.

3.4 PROJECT DEFINITION PHASE

This is the phase in which the vessel to be built is defined in sufficient detail that life cycle costs can be estimated with reasonable accuracy. System and sub-system specifications will be developed and a programme for the required design and development work defined.

It is sometimes broken down into two sub-phases, although the distinction between them can become blurred and depends very much on the contracting policies current at the time. In reality this depends on the point in the process when the supplier is selected.

3.4.1 Preliminary Design

The aim of this sub-phase is to establish the major design features of the vessel that will be built and obtain a clear understanding of the life cycle costs involved. In order to do this the design must be developed in some detail, and a clear procurement strategy is essential. This will have been evolved during the Pre-Feasibility and Feasibility phases. Potential suppliers will become involved, if they are not already, and this may require a contractor assessment and selection procedure to be undertaken. If this is the case, then this sub-phase could merge with the next.

3.4.2 Contract Specification

It is during this sub-phase that the design is completed in sufficient detail to allow satisfactory development contracts to be placed. The level of detail required will depend to some extent on the contracting policies in force and wbetber a single-source supplier is already selected and cooperating with the customer. The assessment and selection of competing bids from suppliers is likely to require a cost and effectiveness assessment itself, as there is now an increasing trend to open up the tendering process to allow potential suppliers more freedom to propose their own solutions. The net effect of this is that the Pre-Feasibility and Feasibility phases and Preliminary Design sub-phase performed by the customer are likely to be validation exercises used to ensure that the tender requirements are realistically achievable within his budget constraints. It is quite possible that a potential supplier may repeat the design phases in responding to the tender, if the requirements are expressed at a more functional rather than physical: implementation level.

3.5 DESIGN AND DEVELOPMENT PHASE

Following contract award the supplier will complete the design of the vessel against the agreed contract specification. During the design and development period there may possibly be changes and alterations which will require consideration and possible specification and contract alterations. These could arise due to changes in operational scenarios leading to revised requirements. It may well be necessary to produce prototypes in order to prove particular sub-systems or even a scaled-down complete craft. If this is the case, there may effectively be a complete procurement cycle required for the prototype itself involving contractor competition, evaluation and selection. With the passing of risk to a prime contractor it is likely that there will be very little change after the Project Definition phase.

3.6 PRODUCTION PHASE

The Production phase is the period during which systematic production of the system is undertaken. In the case of naval vessels, where few units of a particular design are produced and design and construction tend to over&p, the distinction between Design and Development and Production phases is often blurred. It is quite possible that for smaller vessels incorporating unusual features, the first of class effectively becomes a prototype, and series production is delayed pending a trials and evaluation phase. This is unlikely to be the case if a demonstrator has already been used to reduce the technical risks to an acceptable level.

On completion of the first unit, the supplier demonstrates to the customer that the performance specified in the contract requirements has been achieved through a series of trials. These are traditionally geared towards the measurement of detailed measures of performance. It is important that the measures of performance have been correctly identified and specified in the original requirements. Proving overall system effectiveness is often limited to demonstration only. However trials or exercises may be pet-formed that allow correlation with the predicted measures of effectiveness derived during earlier operational and design studies. It is likely that such trials will not be possible until the vessel is fully worked up and operational, but any opportunities for recording and analysis of exercise results should be taken and data fed back in order to validate the assessment models used for future procurement programmes.

3.7 IN SERVICE PHASE

In service exercises will provide opportunities for assessing achieved measures of effectiveness.

During the life of the vessel it will be repaired, updated and possibly completely refitted and rebuilt. The cost-effectiveness of any updates or refits should be assessed in the same way as the original designs. Changed operational requirements may involve new measures of effectiveness, and these should of course be used as the basis for assessing any proposed update. The models and assessment methods used in the initial design could still be used in such an analysis. Alternative solutions are likely to include the do-nothing option, possible updates, or complete replacements. Update options are, however, likely to be more heavily influenced by constraints than the procurement of a new system. Generally the estimates for costs that will be incurred during this phase will be a significant element in cost-effectiveness analyses.

3.8 DISPOSAL

At the end of the vessel's service life it will be disposed of, either sold to another navy, adapted to another role, expended in tests, or scrapped.

There are issues related to disposal that should be considered during the early procurement phases of the ship's life cycle. These could include:

- **Composite hull structures**
- **Toxic substances**

4.0 IMPLEMENTATION

The previous sections have outlined the philosophy behind, and the principles involved in, the conduct of a COEA. The role of such an analysis procedure in the procurement process has also been illustrated.

They have also described how the selection of the hull type should be considered in a whole system context. Studies investigating alternative configurations will be an important element of the Pre-Feasibility phase. It is likely that the range of options will include no more than two alternatives by the Feasibility stage.

The annexes provide information intended to be of use in carrying out a COEA in support of the selection of a hull type for a naval application. They contain design guidance data on several different hull types together with the results of a parametric design study comparing three types over a range of craft sizes and performance levels. This data is of particular use during Pre-Feasibility studies allowing alternative concepts to be compared with a minimum of effort.

The annexes also describe analysis methods that can be used in support of a COEA and provide example applications.

4.1 HULL TYPE DATA

It is assumed that the user of this document will already be familiar with conventional monohull technology. Annex 1 therefore provides a review of the major alternative hull types.

- Air Cushion Vehicle (ACV)
- Surface Effect Ship (SES)
- Small Waterplane Area Twin Hull (SWATH')
- catamaran
- Trimaran
- Hydrofoil

The reviews are not exhaustive but provide sufficient information to illustrate the current state of the art for each class of vehicle. Additional references are given for more detailed data.

4.2 DESIGN CHARTS

Annex 2 presents the results of a parametric design study comparing three hull types

- Monohull
- SES
- SWATH

Designs were produced for a range of payload capacities and performance levels. The study covered the following parameters

- Speeds 20-55kts
- Range 500-4500nm
- Payloads 40-90t

Outputs from the design models used were

- Full load displacement
- Cost (as ratio of baseline design)
- Seakeeping performance (head seas)

4.3 ANALYSIS METHODS

Annex 3 details various methods that can be applied in order to generate data for, and to draw conclusions from, a COEA. Sufficient data is provided to enable an engineer to understand the processes involved and to deal with specialist analysts. Again references are provided that give full descriptions of the detailed application of the methods. The COEA process is still evolving and the implementor has to exercise considerable judgement in deciding which methods to use.

4.4 EXAMPLES

It must be stressed that each COEA is different. It is not necessary to produce vessel designs based on each and every hull type for a particular application, as an initial investigation of each type's strengths and weaknesses will generally eliminate some of the alternatives. Similarly not all the methods will be required to determine a solution to a given selection problem. In order to illustrate this two contrasting case studies are provided in Annex 4.

Although the examples were widely different, in both cases the steps outlined in the main document were followed in order to determine a solution. The choice of methods used in each case were different and were as much a result of the organisation and culture of the decision makers involved as of the characteristics of the particular problem. This serves to illustrate one of the real benefits of the COEA process, that of gaining visibiity for, and commitment from, all parties involved in the resulting decision.

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ANNEX 1.0 - CRAFT TYPES AND DESIGN INFORMATION

The purpose of this annex is to present information to aid the designer in selecting a suitable platform for a warship. The data input into the selection process is shown in figure Al. 1.

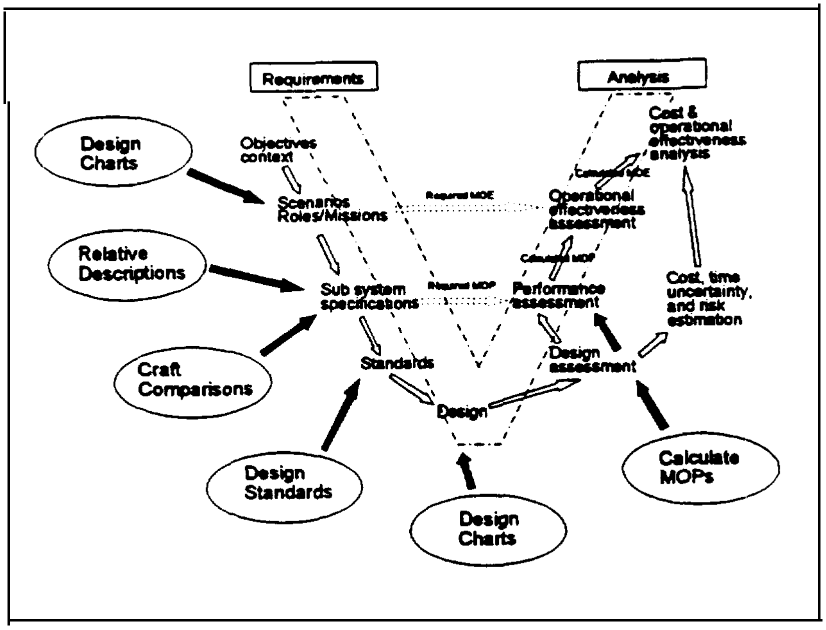


Figure Al.1
Design Data Input to Platform Selection

The annex is divided into six sections describing the following types of unconventional craft:

- Air Cushion Vehicles (ACVs)
- Surface Effect Ships (SESs)
- Small Waterplane Ares Twin Hull (SWATH)
- Catamaran
- Trimaran
- Hydrofoil

Each section covers the same general headings of:

- Introduction
- General Description
- Fundamental Features
- Layout Arrangements
- Resistance and Powering
- Seakeeping
- Structures
- Weights
- Survivability
- State of the Technology
- Overall Advantages and Disadvantages
- Concluding Remarks
- References

NOTE: Figures in this Annex are presented as illustrative only and should not he used for design purposes. Reference should be made to the source literature listed at the end of each section.

Al.1 AIR CUSHION VEHICLES

A1.1.1 Introduction

Air Cushion Vehicles, or ACV's as they are more commonly known, are craft that are wholly supported on a cushion of air. They are therefore more akin to low speed aircraft in their powering and control characteristics.

The review gives overviews of issues to be considered in the design of the hullform and skirt arrangement, describes methods for predicting the performance and seakeeping characteristics and comments on the structural requirements and vehicle weight breakdown. Information is given on the present day state of technology of ACV design,

A1.1.2 General Description

A1.1.2.1 Historical Review

Although ACV is the common generic name for these craft supported completely on a cushion of air, there have been other names historically associated with these vehicles. The original name of hovercraft, used by the inventor, is now more usually used for the light, one or two man, sports machines.

Initially the vehicles were designed without a flexible rubber skirt to retain the cushion, and used instead peripheral jets of air for the same function. Air jets had two major disadvantages, they required a great deal of power for lift, and the vehicles had limited ground clearance. To reduce the power requirement and provide greater body clearance, some craft were designed with solid side walls. A craft type which eventually evolved into the SES.

Another method to achieve the same objective used the now common flexible rubber membrane, or skirt, to contain the cushion and hence reduce the lift airflow requirements. It is this type of vehicle that is the subject of this section

A noted feature of craft with this cushion type is its amphibious capability, although there were hybrid craft with the same cushion arrangement which used marine propulsion and control and were therefore considered to be semi-amphibious.

A1.1.2.2 Vehicle Description

Air Cushion Vehicles (ACV's) are characterised by being entirely supported by a cushion of pressurised air normally retained within a flexible skirt system. The purpose of the cushion of air is to minimise the resistance to motion and to soften the suspension system for operation over waves or rough terrain. The skirt permits: the cushion depth to be increased, but has to be able to provide stability. Cushion pressures are comparatively low (typically less than one-tenth of an atmosphere -ie. below 10kPa or 1.5 psi). Because of this low pressure footprint, ACV's can operate over many surfaces and can therefore be regarded as beii amphibious.

The outstanding features of ACV's are summarised below:

- **High speed**
  An ability to operate at very high speeds due to their low resistance, both overwater and on land.

- **Low Vulnerability**
  The air cushion provides the craft with a low vulnerability to damage from underwater explosions.

- **Low Draught**
  Minimal draught and the lack of surface contact with the hard structure minimises underwater signatures.
- **Amphibious**
  The ACV can operate over land or water.

Military ACV applications include amphibious assault, logistic support and mine countermeasure (MCM) roles, as well as coast-guard and policing duties.

In order to be amphibious it is necessary that such craft are propelled by aerodynamic thrust devices. Due to the minimal surface contact, steering and control features are important. It should also be recognised that such craft have to be lightly constructed. A comprehensive review of the development of ACV's was given in reference 1 and the technology in reference 2.

A1.1.2.2.1 **Propulsion**

Propulsion has been achieved by using:

- **Conventional Air** Propellers or latterly, by using low noise low speed derivatives.

- **Ducted** Fans which make use of a cowl (or duct) around the propeller tips to reduce the impact of the tip generated noise. With careful design this cowl can augment the thrust of the propeller particularly at lower speeds.

- **Ducted** Air usually found on the smaller sizes of ACV craft. This system uses additional lift fans to provide air for craft thrust.

Al.1.2.2.2 **Control**

Since these craft lack any significant ground contact, they are very much affected by the direction of the wind. Control of the ACV has been achieved by:-

- **Conventional Air Rudders** which of course will only work if there should be sufficient air flow across them to provide the necessary forces.

- **Ducted** Air Ports commonly called puff-ports, which allows cushion air to be vented and therefore provide a side force. On some later craft these are rotatable to provide additional craft control.

- Rotatable **Propulsors** these can be either air propellers or ducted fans, and as the name implies the whole propulsor unit rotates to provide thrust in any direction, and therefore provide not only yaw control but also sideforce control.

A1.1.2.2.3 **Cushion**

The characteristics of the cushion retaining flexible skirt provide three very important, and sometimes contradictory, aspects for these ACV's. It will firstly provide the craft with a high structure ground clearance without excessive lift power. Secondly it will give an improved ride over surface irregularities, for example waves. Lastly the cushion must provide the necessary pitch and roll stability. This necessity can sometimes require a degradation in the characteristics needed for optimising the craft ride ability.

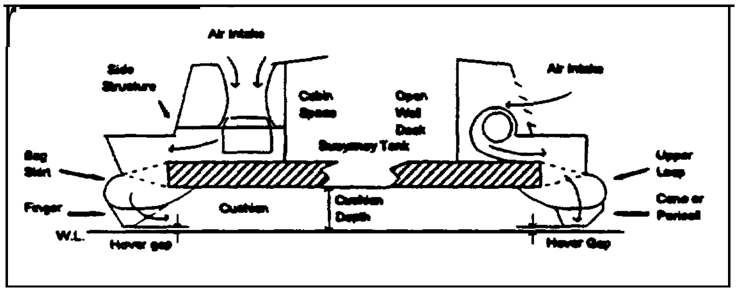
Al. 1.2.2.4 Features

The fully amphibious variants of the ACV do not have any draft restrictions and can operate over, and cross between, any surface. This lack of surface contact also significantly improves the underwater noise signature for these craft. It has also been shown to provide the craft with an extremely high resistance to shock. Only the case where the shock water spout strikes the craft is significant damage likely to be sustained.

A1.1.3 Fundamental Features

A1.1.3.1 Body Shape

The hull form is based on a raft-like platform which provides buoyancy in the event of the need to float. The superstructure is arranged on the upper surface of this buoyancy tank. Various arrangements are possible, usually centred around a cabin or open payload deck. The lift machinery is normally located along the sides of the tank and the propulsion machinery is usually situated towards the rear of the craft, figure A1.1.1.



ACV Configurations
Figure 1.1.1

Because ACV's are susceptible to wind generated forces their design of necessity must consider the implication on manoeuvring control and propulsor and fan intakes.

A1.1.3.1.1 Manoeuvringand Control

The body shape should be configured to reduce to a minimum the effects of wind direction on craft yaw forces. Poor design can result in a cnft which 'weathercocks' and is consequently difficult to control.

The directional stability of an ACV can be high or low. Directional stability is influenced by LCG/TCG dependent hydrodynamic yawing moments and topside configuration dependent aerodynamic yawing moments. For high speed directional control, fins are usually mounted in the slipstream from the propellers and/or the propellers can be mounted on rotatable pylons. Multiple pylon controllable pitch propeller type craft have been demonstrated to bave exceptionally good control, being able to produce both sideforce and yawing moments. However, such systems are rather complicated and expensive.

For control at low speeds, combinations of puff ports, swivelling bow thrusters and skirt lift devices are often employed. Such devices rely on diverting pressurised air from the lift system, which due to its low pressure provides for quiet operation but cannot be expected to generate large control forces. However, these are commonly fitted to most of today's types of craft

Al. 1.3.1.2 Lift Fan and Propulsor Inflow

The lift fans are normally conventional centrifugal type, since these are relatively simple and inexpensive. Peak total efficiencies are high (up to 85%) and the pressure/flow characteristics appear well able to cope with the demands of rough water or overland operations. Few problems have been experienced with fan stall. Intake and ducting losses may account for as much as 35% of the fan static head and this needs to be considered in the total lift power equation. Light weight centrifugal fans are capable of generating static heads of up to 16kPa. Large craft operating at high weights may therefore require special fans operating at higher rotational speeds. Mixed flow type fans have been considered for such purposes.

It is essential that any high yaw angle experienced by the craft, or large relative wind angle, does not cause significant performance loss in either lift fans or propulsor. Such a requirement usually imposes considerable restraints on body shape and fan and propulsor positioning.

A1.1.3.1.3 Hydrodynamic Loads

Although nominally clear of the surface there are occasions when structural impact can occur. The first occurs during normal operation in waves and in such cases the cushion absorbs some of the energy. Of a more serious nature is the occasion when there is a failure of either the lift system or the bow skirt cannot maintain its geometry. In either case the craft 'ploughs in' with considerable wave impact on the forward structure. Shaping the leading edge of the structure can considerably alleviate these loads, and also provide a hydrodynamic lift to force the structure clear of the water.

A1.1.3.1.4 Cushion Geometry

In order to ease the transition from the end to the side skirts it is necessary that the structure planform has rounded corners. This feature will however create its own problems which can seriously affect the skirt geometry unless these changing cushion forces are recognised and their effect designed out.

A1.1.3.2 Cushion System

The flexible skirts that contain and comprise the ACV air cushion, are of three primary types. All three provide the craft stability to compensate for pitch and roll motions, which will be discussed in Section Al. 1.3.5.

Al. 1.3.2.1 Compartmented Cushion

This was an early arrangement which had a bag type of peripheral skirt and a compartmented cushion using inflated longitudinal keels and transverse dividers. This type of cushion generates the craft stability by reason of differential pressure within the cushion compartments.

Al. 1.3.2.2 Jupes

This cushion system comprised a number of individual cells and represents a more extreme example of the compartmented cushion. It suffers from having a large number of trailing edges to the cushion components. Any trailing edge, particularly in a flexible material, is prone to the problem of scooping water, which seriously degrades skirt life in these areas.

Al.1.3.2.3 Peripheral Loop

The peripheral loop skirt was a development which eliminated the inflatable keels and transverse dividers, and consequently reduced the amount of maintenance required. Because of their simpler construction, skirts of these types had lower loop/cushion pressure ratios which therefore required less lift power, and also were contributory in improving the craft ride.

Cushions contained by peripheral loop systems create craft stability, in pitch and roll, by causing a shift to occur of the cushion centre of pressure.

The pressure in the cushion in determined by the weight of the craft acting over the cushion area. The pressures in the upper loops or bags are generally between 20 and 3596 above cushion pressure. The fans have to be able to provide this pressure at a flow rate dependent upon the hover gap which in turn depends not only on the craft size but also on the design requirements. The cushion air flow rate of current commercial ACV types is very approximately given by:

Cushion Flow rate $(m^3/s) = 5.2W^{0.75}$

Cushion + Bow Thruster Flow Rate $(m^3/s) = 9.0W^{0.75}$

where W is the all-up-weight (t)

This equation shows that the flow rate does not increase proportionally with weight, primarily since the hover gap does not have to be increased linearly with craft size. This cushion flow includes an allowance for extra air that may have to be provided for bow thruster and other control devices.

A1.1.3.3 Craft Length/Beam Ratio

ACV's generally have low length/beam ratios unlike other air cushion craft, such as the SES, which has higher ratios. Although the wave making drag, which is to be discussed in Section A1. 1.5, shows marked improvements with longer craft, other aspects of the ACV design demand the lower aspect ratios.

- As has been previously said, the craft are very susceptible to wind direction. This invariably requires the craft to yaw relative to their direction of travel, and therefore the effective length reduces. The optimum from this aspect would be a circular craft whose length/beam ratio would be constant at any yaw.

- Cushion generated restoring forces tend to be low in order to improve the craft ride. Consequently the vehicle needs to have a wide beam to generate the stability requirements.

Experience has shown that ACV's with cushion length/beam ratios of around 2 - 2.5 meet the requirements, particularly since the yaw angles at speed are not very large.

A1.1.3.4 Lift System

A1.1.3.4.1 Wave Pumping

The ACV lift system relies on the ability of the flexible skirt to seal the air gap at the periphery of the cushion to reduce the power requirements. On surfaces which are not very rough the air flow, and therefore, power required for lift need not be large.

Craft operation in wave height of half cushion depth, or greater, has been found to require proportionally more air flow. Under these conditions a condition defined as wave pumping becomes the factor which determines the volume of lift air. It was found that to provide an adequate ride response the cushion lift system needs to supply sufficient air to replenish the volume of air pumped by the waves. Simplified this equates the cushion air flow to craft speed x wave height x cushion beam. It was also obvious that for the same reason the lift air needed to be supplied to the cushion at or near the craft bow.

Al. 1.3.4.2 Loop/Cushion Pressure Ratio

Both the compartmented bag type, and peripheral loop cushion systems rely on the pressure differential of the bag, or loop, to the cushion pressure to maintain the skirt geometry. This is particularly true when the skirt is subjected to water drag forces, from waves for example, which are tending to deform it. Generally the bag type skirt had higher bag/cushion pressure ratios than the peripheral loop derivative. This resulted in lower lift powering requirements for the latter, and also provided, its adherents would claim, a softer ride. For either cushion type this pressure ratio was vital in maintaining the craft stability requirements.

A1.1.3.4.3 Fan Characteristics

It is apparent that the variation of cushion lift flow when operating in waves would affect the lift fan characteristics. In the interests of not degrading the ride of the ACV the lift fin should not provide large changes of head with changes in flow.

A1.1.3.5 Craft Stability

In the case of the ACV, craft stability requirements can only be generated from the cushion, although there have been a small number of vehicles which have used aerodynamic controls to provide a pitch trim capability.

In order to maintain adequate roll stability, the depth of the cushion as a general rule, should not exceed 20% of the cushion width. Since adequate width is important for ACV stability, length/beam ratios are usually low (typically around 2.0 to 2.5). In general, stiffness values of at least 3% lateral CG shift per degree of roll should he maintained. Small craft have in the past overturned, and hence this aspect of roll stability is important. It is usual to restrict the speed of a craft when subjected to lateral drift and particularly in high-rate turns.

A further aspect of instability is that known as “plow-in”, which can result in trim down and rapid deceleration as the bow seal is dragged under at high speed, see references 3 and 4. Plow-in can he avoided by careful design of the bow seal geometry and choice of operating pressure ratio combined with the choice of LCG location. Transverse cushion divider skirts can also be fitted to improve longitudinal stability by maintaining a forward/aft pressure differential. Generally the “plow-in” boundary should be kept outside the craft performance envelope.

Skirt bounce can also sometimes occur. Although more a nuisance than dangerous, this is caused by pressure/flow instabilities and results in an unpleasant heave motion which occurs at low craft speeds. A relatively simple cure can be obtained by fitting additional vertical webs into the skirt bags or loops, which damp such oscillations.

Al.l.3.5.1 Compartmented Cushion

Craft with these type of cushion systems rely on differential pressures across the cushion to provide the restoring forces. Quartering tbe cushion with flexible dividers provides for both pitch and roll. See figure Al. 1.2 for a typical example.

A1.1.3.5.2 Peripheral Loop

Cushion systems of this type do not have any flexible cushion dividers and can therefore only rely on a change, and shifts, of cushion area to generate their stability requirements.

This is usually achieved by the combination of two effects.

- Deformation of the cushion segment
- A geometry shift of the loop and segment

These two conditions are interrelated, deformation of the segments creating an imbalance of forces which consequently forces the loop to change shape (figure Al. 1.2).

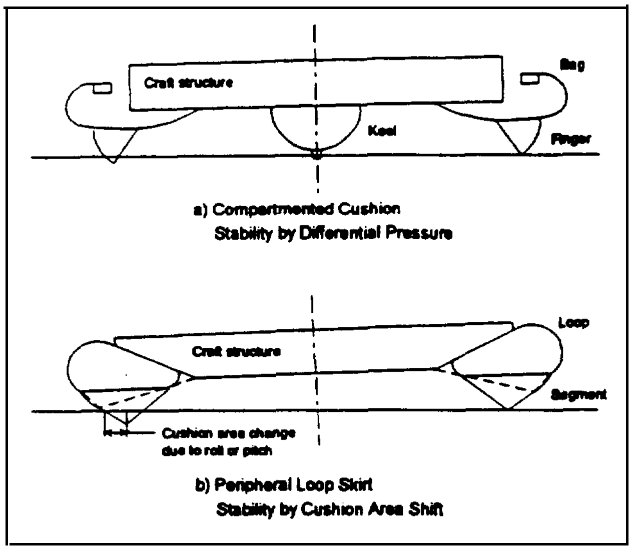


Figure A1.1.2
Typical Cushion Stability Measures

A1.1.3.6 <u>Operating Speed Range</u>

Due to low resistance characteristics of ACV's, operating speeds are normally high (frequently in excess of 50 knots). Air propeller type propulsion is normally employed and high speeds are only really limited by the installed power and the need to navigate safely. However, it should be understood that such high speeds are only attainable in low sea state and wind conditions. Not only does the craft resistance increase proportionally more rapidly in waves than is typical of other forms of unconventional craft, but the thrust from the propellers is dependent upon the air speed. In head winds this is likely to cause a significant loss of thrust in comparison to water propelled craft. For example, a craft designed with a top speed of 60 knots, may only achieve half this speed in strong headwinds and waves of about cushion depth. In following winds the opposite is, of course, the situation. Non amphibious craft using waterscrew or waterjet propulsion will not experience this effect.

At lower speeds required for MCM operations the resistance is characterised by humps and hollows in the wavemaking drag versus speed curve. At such speeds, wavemaking accounts for as much as 80% of the total resistance. In the design of ACV MCM craft it is therefore a consideration to select a craft length which equates with a Froude number at the design speed, which allows operations close to a minimum in the resistance curve. It should be appreciated that where the slope of tbe resistance curve is negative, there will be unstable speed zones wbere it will not be possible to operate. In addition, operation between the primary and secondary humps can result in high levels of deck wetness. Selection of the correct design speed is thus a trade off.

A1.1.4 Layout Arrangements

The primary consideration in assessing any arrangement is the proposed duty. If, for example, vehicles are to be carried this usually constrains the design to a significant extent, particularly for a single deck craft. In this context it should be remembered that one of the largest vehicle carrying ACV's built, ie. British Hovercraft Corporation N4, was single deck with only the control cabin mounted on the top of the main structure.

A1.1.4.1 Machinery

Power has of course to be provided for both the lift and thrust systems. In a number of designs an integrated drive has been installed whereby the engine output is directed through a splitter gearbox to both a fan and to a propeller. The thrust power can be varied by adjustment of the propeller pitch. For most military and passenger craft, lift and propulsion are integrated which often permits the use of fewer engines resulting in reduced complexity and cost. Sometimes separate engines are installed for lift and thrust, and these can be positioned as required on the buoyancy tank top. This can sometimes allow a more flexible arrangement, particularly suitable for low speed operations when gas turbines are used. Protection of the engines against the ingestion of salt water spray or sand and dust overland, is a very important aspect of the installation. Various types of filtration and coalescence systems are employed. AU the machinery driving such units has of course to be air cooled or radiator cooled, since there is no simple way of picking-up sea water for cooling purposes. This currently limits the size of suitable lightweight diesel engines. The availability of marine gas turbines extends this power limit considerably.

Cushion type tends to dictate the position of the lift fans. Peripheral loop designs require a large airflow near the bow, and therefore the lift fans tend to be at the same place. Compartmented cushion designs require equal flows to each section. For both types of craft ducting has been used to distribute the flow but will lead to additional lift losses.

The other factor influencing the machinery packages relates to the propulsors. There are always technical limitations on the size of air propulsor, it's operating clearances and on its power capability at any point in time. These limitations, particularly for larger craft, tend to define the number of propulsors needed.

Combining the lift fan requirements with the propulsors and available engines then forces particular machinery arrangements.

A1.1.4.2 Accommodation

Accommodation spaces on ACV's are normally arranged on the upper surface of the buoyancy tank within a single deck height, although the level of the control cabin and passenger cabins on a car ferry are sometimes raised slightly. The need to restrict the vertical CG height in order to comply with stability requirements should be borne in mind as is the situation for all marine craft.

The trim of ACV's is also more sensitive to payload positioning than on other forms of unconventional craft. A careful balance has to be maintained and it is normal to inwrporate a fuel or water ballast transfer system capable of moving the horizontal CG by about 5% of the craft's length or beam.

The accommodation should be located away from machinery spaces for both noise and safety reasons. The accommodation layout allows for greater flexibility than is the case for most other craft.

In ACV's used for commercial applications the requirement to carry a large number of personnel limits any arrangement specifically for ride considerations. Military designs with fewer personnel on the other hand have greater latitude in this respect.

It has been found that ACV's, particularly peripheral loop designs, are not so susceptible to ride degradation at the extremes of the craft.

A1.1.4.3 Deck Space

Military ACV's which tend to have a dense payload require to have planform (cushion) area larger than required purely for the payload and accommodation in order to limit the cushion pressure. In these circumstances there is deck area available for armaments and boats etc. It is usually possible to arrange the layout of an ACV with at least 50% of its platform area available as deck space, and some craft have been built with large open well decks.

ACV's generate considerable spray, especially at low speeds. Although spray suppression skirts can be fitted that are very effective, it should be expected that open and exposed deck areas will be wetted and difficult to work on. With the craft floating on the surface, freeboard levels are low and this may ease the deployment/recovery of overboard equipment, and of course in this case, there will be no spray. It is unusual for an ACV to hover steadily at an intermediate height because the cushion is not sufficiently stable. On cushion the ACV is likely to have considerable freeboard which would make boat operations difficult, particularly with the inflated cushion in the way.

A1.1.4.4 Habitability

Habitability requirements on an ACV tend to be short-term. Loiter capability on cushion is limited by the quantity of fuel that can be carried. The alternative is to drop off cushion and float as a raft.

Military ACV's because of the limited crew numbers can be designed with the control and operational centres at positions of greatest ride comfort. This is usually within the centre third of the vehicle, although as stated earlier, craft with peripheral loop cushion designs do not have their ride characteristics significantly degraded outside these limits.

Off cushion the craft is very stiff, and is likely to exhibit uncomfortable ride characteristics in any sort of seaway.

Noise levels from machinery generally stay high because of the requirement to maintain the cushion. Due to the compact design of most ACV's it is extremely difficult to insulate the noise sources of fans, engines, gearboxes, and propulsors, from the accommodation areas.

A1.1.5 Resistance and Powering

A1.1.5.1 Resistance

The ACV being a hybrid, that is operating at high speed in air, and overwater, has components of drag resistance common to both aircraft and ships. These are generally defined as:-

- Wavemaking Drag Resistance
  This component of craft resistance is common to both ACV's and ships, and in both cases is greatly influenced by craft length. In the case of an ACV the cushion pressure has a significant effect. Shallow water also has a significant effect and can increase the drag sufficiently to cause operational difficulties.

An important feature of this drag component is that it reaches a peak at a Froude number (of approximately) 0.7 and then significantly reduces, a feature which most ACV's are designed to exploit, (figure A1.1.3). The length/beam ratio also significantly affects this component of drag. Increasing this ratio reduces the height of the peak, and also shifts it to higher Froude numbers.

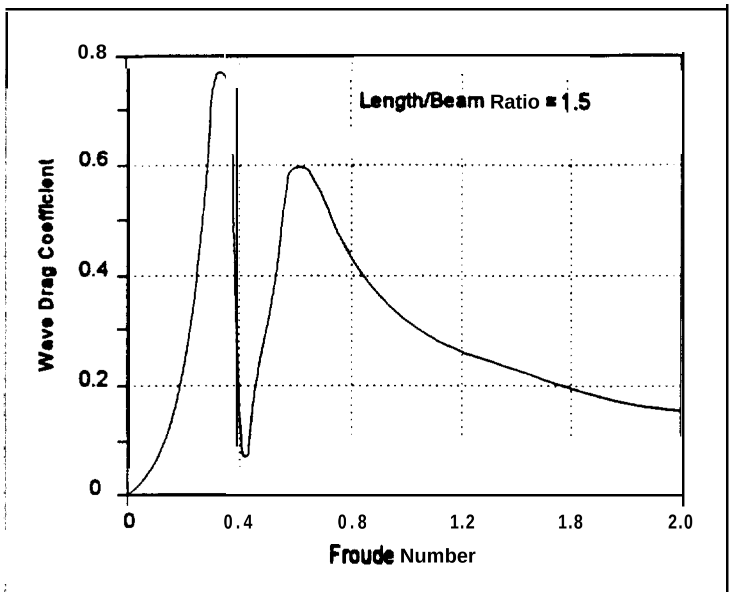


Figure A1.1.3
Typical Wavemaking Drag Curve

It should be understood that the pressure field below the craft will generate surface waves which will cause the craft to trim. In simplistic terms this trim acts like an inclined plane and hence causes increased resistance to motion. The topic has been extensively researched and is well summarised in reference 5.

- Aerodynamic Drag

  This component of drag is proportional to the (relative wind velocity)^2 and is usually minimised by keeping the external craft shape smooth, clean from protuberances, and having a small frontal area.

- **Momentum Drag**

  This is derived from changing the direction of flow of the cushion lift air and is proportional to the craft relative wind velocity. It is important that there is a smooth airflow to the lift fans to minimise air flow breakaway.

- **Skirt Drag**

  The fully skirted ACV, whether bag, or peripheral loop, will always have some contact with the surface. It is this contact and spray which creates this component of drag. Overwater this contact is increased because of the self generated pressure waves created by the cushion.

- **Wave Drag**

  Operation over rough surfaces, particularly in waves, will create an additional skirt drag. Over water it not only causes an increase in the skirt wetted area, but also causes local deformation of the cushion segments which consequently have a tendency to scoop. Both of these phenomena cause an increase in the craft drag.

- **Total Drag**
  Combining the components of drag results in the typical characteristic of figure Al. 1.4. It should be noted that typically there is a region where craft speed cannot be maintained. In this unstable region a small increase in drag will cause the ACV to decelerate into a region of higher drag.

  The total resistance of an ACV is calm water at about 50 knots, is very approximately 60% of an equivalent sized SES, or about 40% of that of an equivalent sized catamaran.

Although current prediction methods are very accurate it is usual to carry out model tests to verify total resistance estimates.

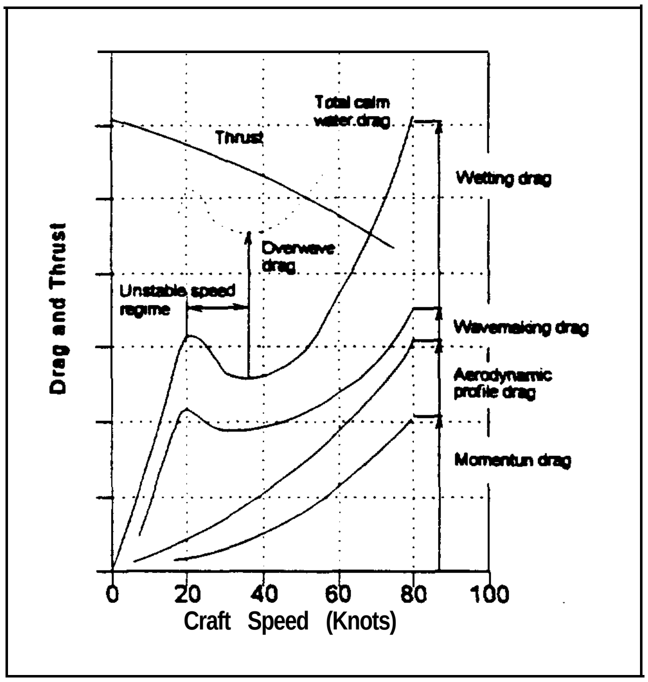


Figure A1.1.4
Drag **Breakdown of Typical**
Large Air Cushion Craft

- **Overwave Resistance and Speed Lass**
  In waves, added resistance is incurred mainly due to motions and the additional wetting of the skirt. Although there are no reliable methods of theoretically predicting the added resistance in waves, semicmpirical methods have been shown to be adequate.

  As mentioned in section 1.1.3.6, the thrust generated by air propellers is dependent upon the craft's air speed, and hence in head wind conditions significant speed losses will occur. Such losses are of course less severe on across wind headings with a significant gain in following winds. Published data (reference 6) suggests that a craft designed for high speed in calm water will lose about 50% of its speed in head seas with a significant wave height equivalent to its cushion depth. In beam seas the reduction was only 20%.

A1.1.5.2 Craft Geometry

Craft **planform geometry** can have a significant influence on the components of drag as defined earlier. A longer thinner craft can have much reduced wavemaking drag, and by virtue of a smaller frontal area, a lower aerodynamic drag. Usually however the requirements of stability dictate the necessary length/beam ratio, which therefore can impose a performance **penalty.**

A1.1.5.3 Propulsion

The low resistance characteristics of **ACV's** is more than **offset** by the low PC of airscrews except at high **speeds greater than 60 knots. The power required to sustain the lift system (see section 1.1.3.4) has to be** added for the total installed power requirement.

Airscrew propulsion is normally employed, either as **aircraft-type** "open" propellers or **ducted** (or shrouded) propellers. It is desirable in both applications to ensure **undisturbed** uniform inflow into the propeller disc. At a given diameter and power, **ducted** propellers generate about 30% more thrust at low speeds and hence are more suitable **for** applications which require high manoeuvrability (eg. MCM roles). At high speed (SO knots for example) however, there is less difference in performance between "open" and **ducted** propellers, and overall propulsion efficiencies of between 40 to SO% are typically obtained. Typical propulsion performance is shown in figure Al. 1.5.

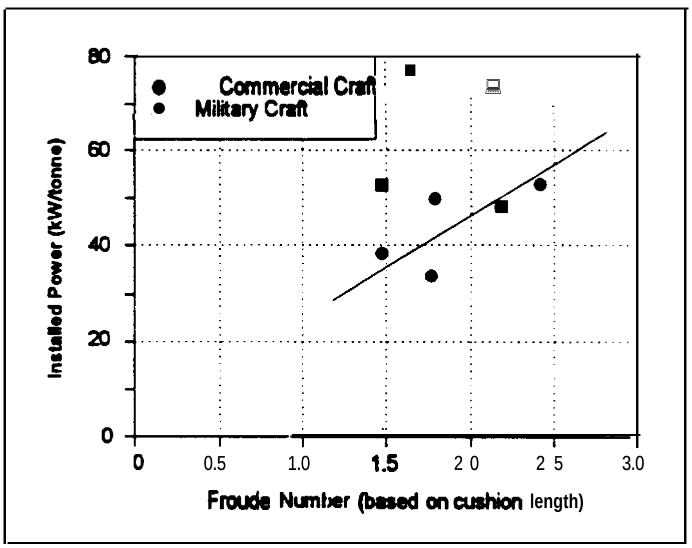


Figure A1.1.5
ACV Installed Powers

In general any of the methods of air propulsion provide a degrading thrust level with speed, see figure Al.1.4.

One feature **of this phenomenon** is that the propulsor provides a greater thrust capability at the craft hump speed. This feature is essential to provide a good **overwave** performance and ensure the ACV does not operate within the unstable speed range also **shown** in figure Al. 1.4.

The **decrease** in **propulsor** thrust level with **forward** air **speed, coupled** with increases in the drag **components** with air speed, **result** in **the** ACV performance **being** very seriously degraded by head winds. Tail winds on the other hand do not result in a **corresponding** improvement in performance because of other considerations, eg. **hydrodynamic** wave drag.

A1.1.6 Seakeeping

Seakeeping capabilities of the ACV are dependent on a number of conditions.

These are:

- Height of waves relative to the cushion depth.
- Wavelength and therefore wave speed which coupled to the craft speed determines the encounter frequency.
- Cushion type although this is probably less quantifiable, it has been suggested that the peripheral loop type provides a softer ride.
- Cushion stiffness in pitch, roll, and heave are the features which determine the ACV stability parameters. High levels of stiffness result in a harder ride, ie. higher acceleration levels.
- Lift fan characteristic, which must maintain the fluctuating lift air volume flow without excessive changes in pressure.

In respect of the wave height capability ACV are generally designed to operate in waves of a half to three quarters of the cushion depth. Some peripherally skirted ACV's have operated successfully in waves higher than this without detriment. This was achieved by providing sufficient lift air to resupply the cushion when pumped by waves, as described in Section Al. 1.3.4.1. Generally motion levels have been found to be tolerable in wave heights up to cushion depth depending on forward speed and heading to waves. Operation in waves whose length is longer than the ACV leads to the craft following the wave surface, that is, contouring. Unfortunately there is a limit to how quickly the craft can contour and still maintain acceptable limits for the operating personnel. The ride in low sea states is better than for an SES without the 'cobblestoning" type motion. Ride control systems are not normally fitted to ACVs.

A1.1.7 Structures

A1.1.7.1

The hull structure traditionally followed aircraft practices in being manufactured from aluminium, albeit marine grade, with rivetted construction. The reason was principally to minimise the structure weight and therefore the lift power and the related momentum and wavemaking drags. Advances in manufacturing led to practical designs being considered in welded aluminium and glass reinforced polyester (GRP). Higher structure weight fractions for those craft being offset by lower cost production.

A1.1.7.2 Skirt

These are usually manufactured from flexible nylon filaments woven into a cloth which is then covered by a proofing coating such as a rubber or neoprene compound. There are several aspects of the skirt mechanical design which need to be considered.

- Mechanical joints between segment and loop and to the structure need to be reinforced to eliminate stress concentrations.
- Skirt materials need to have adequate fatigue life in the reinforcing fibres and the coating should not readily detach from the fibres (delamination).
- The loop should be designed to maximise the warp strength by using lengths of material down the cushion. The joii created in the loop by 'using this technique also provides rip stops which limit any tears along the loop.

Most development has been carried out witb "bag and finger" type skirts and these are the more commonly used on present day craft. If properly designed and manufactured, the bags should last many thousands of operational hours, but the fingers have to be replaced more often. Finger wear rates are dependent upon craft speed and the amount of time spent operating overland, particularly over rough terrain. In general the average finger life on commercially operated craft is about 400 hours of underway operation. Fingers along the side skirt, especially toward the stern suffer the greatest wear, and bow fingers the least.

Various forms of stem skirts are used, the most common having cones fitted below bags instead of fingers. The operational life of these cones is often less than that of the side fingers.

The static loads in skirt bags can be predicted from the inflated geometries. Dynamic forces can increase the static loading by as much as four to six **times.** Loads in fingers and their attachments are much more difficult to predict and their design is largely based on operational experience.

A1.1.7.3 Skirt Design

As discussed earlier the peripheral loop skirt does not have the inflatable cushion dividers of the compartmented cushion. It can therefore with careful design be accessed from outside the cushion, unlike the cushion dividers which are underneath the craft. This feature greatly improves the maintainability of the skirt.

A1.1.7.3.1 Peripheral Loop Design

There are features of the peripheral loop skirt which must be considered. Some like the loop/cushion pressure ratio have been discussed previously and have a significant effect on cushion geometry.

- Segment Attachment
  Some designs have the segment inner connection attached to the hard structure by wire stops, or fabric sheets, see figures Al. 1.6 a, b and c.

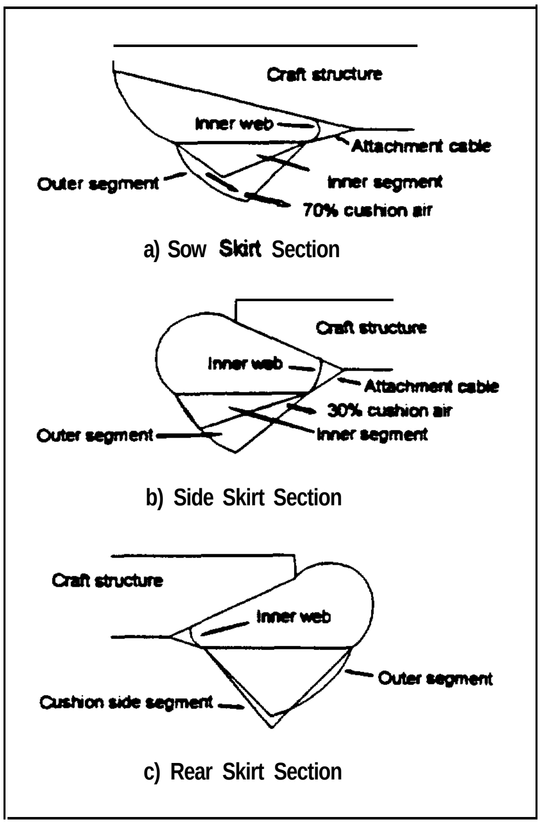


Figure A1.1.6
Typical Peripheral Loop Skirt Sections

ACV cushions using this design are susceptible to skirt geometry changes resulting from pressure fluctuations and drag influences. Improvements to the design can be achieved by connecting the segments to the hard structure figure Al. 1.7.

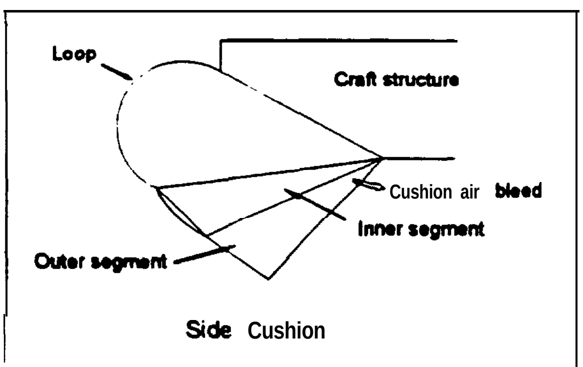


Figure A1.1.7
Typical Deep Cushion Skirt Sections

Changes in loop tension quickly compensate for increased segment drag. This is particularly true for the bow skirt where wave drag has considerable effect.

- **Corner Design**
  In order to maintain a level hemline, ie. segment loop attachment line, cognisance should be made of the different loop loading conditions at the cushion corners. These are rounded in planform to continue the peripheral loop tensions, and in consequence the resulting triangular segment shape reduces the segment loading.

A1.1.7.4 **Superstructure**

In order to maintain the high speed potential of ACV's it is important to minimise structural weight. The primary structural component is the buoyancy tank, which is usually designed as a multi-cell raft. Welded aluminium alloy is normally the chosen method of construction. The upper deck is adequately stiffened to support a vehicle payload and tie-down points are usually added in order to restrain any movement whilst the craft is at speed.

The superstructure is also usually of welded aluminium alloy, although fibre-reinforced plastic materials have also been used in some designs. Similar lightweight materials are employed in the construction of the fans, and propulsor pylons and ducts, etc.

Few Classification Societies offer specific guidance on ACV structures, particularly with regards to skirt design. However, the British Hovercraft Safety Regulations (reference 12) do give advice on the likely loads and structures are normally designed from first principles.

A1.1.7.5 **Local Strength**

The local strength in components such as the skirt attachment points, support of control devices and machinery foundations, requires consideration. Vibration loads generated by rotating components are of concern, especially around fans and propulsors.

Results from underwater explosion trials have confirmed the low vulnerability of ACV's to shock damage. The cushion appears to be able to absorb the transmitted pressure pulse and the only serious effects have resulted from the impact of the water plume or local damage caused by falling debris.

A1.1.8 **Weights**

ACV's are sensitive to weight although the early extreme measures taken in the interests of minimising weight are no longer so evident. Structures are now manufactured from GRP or welded aluminium rather than the light aircraft rivetted aluminium. Choice of engine has changed as well, with early craft almost exclusively using gas turbines which of course have a high power to weight ratio. Later commercial craft have made use of high speed diesels, although military ACV craft still almost exclusively use gas turbines. The weight of the hulls of ACV's built using a welded aluminium alloy form of construction, can be estimated for general design purposes based on a structural density of about 35kg/m^3. To this must be added the weight of the machinery and ouffit and the weight of the skirts.

Skirt materials vary with application and craft size. In general, the materials used for the manufacture of bags or loops can be estimated from:

$$\text{Material Weight } (kg/m^2) = 0.75.W^{0.25}$$

where W is the craft all-up-weight (t)

Finger material weights are generally about 20% heavier than those needed to manufacture the bags. The above relationship would give a total skirt weight for a 30m long ACV of about 6t.

Payload weight fractions are particularly high and existing craft carry disposable loads (ie. payload plus fuel) of up to 50% of their all-up-weights. This is significantly higher than that achieved by other forms of unconventional craft.

Although the cushion pressure is directly related to the craft's weight this only has a secondary effect on performance, since the cushion wavemaking drag is a minor component at high speed (see Figure Al. 1. 4). At a given fan power, the increase in pressure will be associated with a reduction in air flow rate, hence reducing the momentum drag. Therefore the only significant cause of increase of resistance with weight is additional skirt drag.

The loss in waterspeed of ACV's due to weight increase is therefore small and probably less than that associated with other forms of unconventional craft. To a first order approximation a loss of about 1% in waterspeed for a 4% increase in weight, may be assumed over moderate weight changes.

Performance overland however, is more seriously affected by weight increase, since skirt drag is higher due to the unevenness of the terrain. The thrust required to maintain station on a smooth gradient will be directly proportional to any weight increase. Thrust power is often dictated by overland slope-climbing requirements.

A1.1.9 Survivability

Survivability must be approached in two ways. Firstly in the ability of the military ACV to avoid detection or hit, that is its susceptibility, and secondly the ability to sustain damage and remain operational, that is vulnerability.

A1.1.9.1 Susceptibility

In a military role there are four craft signatures that are generally used:-

- Magnetic

  This signature is usually inherently low since most ACV's arc designed to minimise the structure weight which usually implies the use of non-magnetic materials. Any major ferric, and therefore magnetic, items are high above the water surface when the ACV is on cushion. The magnetic signature is consequently low due to the cube law fall off with distance.

- **Infra-Red**

  The high lift and propulsive power requirement for the ACV will probably result in large infra-red (IR) signatures. Although exhausting the engines into the cushion has been proposed as a means of reducing this signature, it will create backpressures which will derate the engine performance, and in any case is not practicable with gas turbii.

  Any other form of IR suppression will add to the structure weight.

- Radar

  The generally accepted means to reduce the radar cross section area can be readily carried out on the structure. However, the sharp edges where the flat panels join can readily cause airflow breakaway and adversely affect control requirements and craft drag levels.

  Air propulsors on the other hand cannot readily be concealed from radar, even with the use of composite blades.

- Noise

  Noise signatures usually relate to the level transmitted into the water. In this respect the cushion of the ACV and its lack of hard structure contact provides a considerable degree of noise isolation.

  Airborne noise from the propulsors can be a problem both within the craft and externally. Measures like shrouded propellers can significantly reduce airborne noise levels.

A1.1.9.2 Vulnerability

Tests on ACV's have shown that the cushion provides an effective method of attenuating shock damage from underwater explosions. Problems occur only if the plume from the explosion rises directly beneath the craft.

Typically ACV's have a raft comprising many watertight compartments. This type of structure results in a craft which is very difficult to sink.

Flexible skirts which at first sight may be considered to be vulnerable to damage can sustain quite considerable damage to the loop or segments and remain operable.

A1.1.10 State of the Technology

A considerable number of ACV's have been built up to a size of 56.4m and gross weights of 300 tonnes. These have ranged in duty from higher speed commercial passenger and vehicle carriers, tank landing craft, and slow speed arctic transporters. The most successful of these craft have exploited the ACV's amphibious capability. This is part explanation of why there were very few military variants, although several conversions of civilian designs to military usage have been tied. Data accumulated from these craft now provide a firm basis for the design of future craft, not only for this size range but also for extrapolation to larger sixes. Limiting design constraints would probably be associated with the propulsor sire and power loadings technically feasible.

Methods of construction have evolved over the years, and although weight is of paramount importance, alternative more cost efficient structures have been successfully used. These have included the use of welded aluminium and Glass Reinforced Polyester (GRP). Production methods for the structure are therefore well established and can be suited to the design requirement.

Skirt construction techniques and materials have also evolved to the stage where reasonably low maintenance and cushion life is readily achievable.

A.1.1.11 Overall Advantages and Disadvantges

The ACV has several features which can prove to be advantageous for specific roles.

A1.1.11.1 Advantages

- High speed capability
- Transit between water and land possible
- Operation over any surface - water, marsh, snow, ice or sand
- Provide a good ride in waves up to cushion depth
- Cushion provides good isolation for underwater noise signature
- Similarly the cushion reduces shock loads from underwater explosions
- Good manoeuvrabiity with appropriate thrusters

A1.1.11.2 **Disadvantages**

- Lift power fuel requirement limits the ACV loiter capability
- Precise control difficult to achieve
- Significantly affected by wind speed and direction
- Significantly affected by weight growth
- Craft performance and control sensitive to trim changes
- High build and maintenance costs

A1.1.12 **Concluding Remarks**

The preceding pages are designed to provide guidance on the features required of an Air Cushion Vehicle. There are many publications which detail particular design considerations, and there are sometimes differences between authors.

It can be said that the ACV provides particularly useful specialist features, but unfortunately has several areas which are not so useful and therefore make it fail to be a general all round vehicle.

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Al.2 SES

A1.2.1 Introduction

This document offers guidance on the procedures and techniques for concept or preliminary design of SES types of unconventional craft. The review gives overviews of the hullform and layout arrangements, describes the performance and seakeeping characteristics and comments on the structural requirements and vehicle weights.

The review places emphasis on military design requirements and the roles likely to be undertaken by SES. A general appraisal of likely operational advantages is given together with information on the present day state of technology, although this is mainly based on commercial craft operations.

A1.2.2 General Description

Surface Effect Ships (or SES) have catamaran type twin hulls, but are primarily supported on an air cushion generated by lift fans. The cushion is restrained between the sidehulls and flexible seals at the bow and stern. A typical arrangement is shown in the upper part of figure A1.2.1. This shows propeller propulsion but waterjets are frequently used as an alternative.

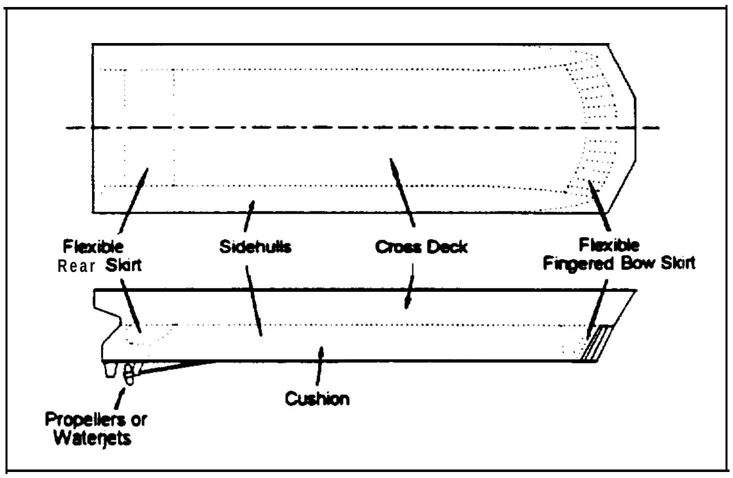


Figure A1.2.1
Typical Arrangements of SES Craft

The outstanding features of SES are summarized below:

- **An ability to operate** at high speeds due to their low resistance.
- A shallow draught compared to other hullborne vessels.
- Reduced underwater signature levels.
- Improved shock hardness to underwater explosions.

In the &sign of SES it is important to minimise the craft weight since this directly influences the cushion pressure, resistance, propulsion power and the power required for the lift system. The cushion also has an important influence on the stability of the craft.

SES have been considered for fast combatant and anti-submarine warfare (ASW) roles. They also have particular application for mine countermeasures (MCM) due to their low signatures and reduced vulnerability, and a series of such craft is now in production.

A1.2.3 Fundamental features

A1.2.3.1 Hullform and Cushion System

A comprehensive worldwide review of SES is given in reference 1, and covers the current state-of-the-art of these vehicles.

As a general rule, in order to obtain a good performance the depth of the cushion under an SES should be about 50% greater than the significant wave height of the design specification sea state. The length/beam ratio of the cushion has a large influence on the resistance (see section A1.2.5.1) and the beam has to be of sufficient width to maintain stability (Section A1.2.3.2).

The sidehulls need to be slender but are generally wide enough to contain the propulsion machinery. A typical cross-section is shown in figure A1.2.2.

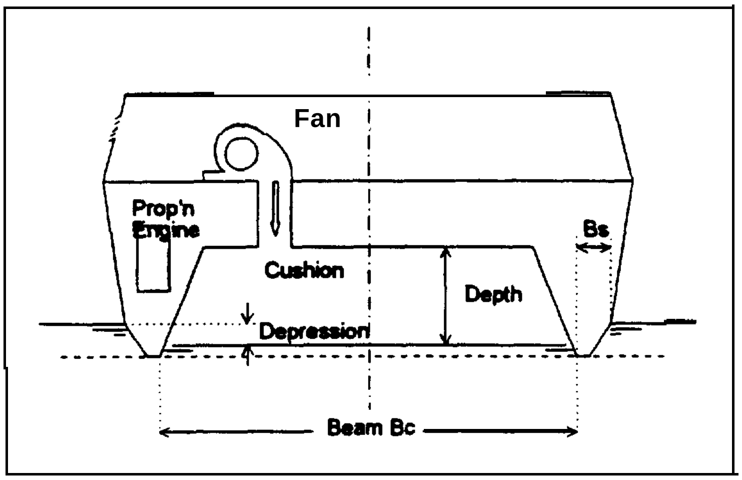


Figure A1.2.2
Typical SES Cross Section

The lower sidehulls have to be carefully shaped to reduce wetted area, but also have to support a propeller arrangement or encompass a waterjet inlet and pump flange.

Since the sidehulls have to be in contact with the water surface in order to seal the cushion, they do provide some supporting buoyancy (typically carrying 20% of the craft's weight in calm water). The remaining weight is carried by the cushion and its pressure can be simply estimated from the weight supported over the planform area. Cushion pressures are relatively low, typically being less than 10kPa (one-tenth of an atmosphere).

The cushion is retained between flexible seals forward and aft (see section A1.2.7.1). These extend to the full cushion depth but have to be able to yield to seas passing through the cushion in overwave operation. The design of seals is critical, not only of their inflated geometry but in respect of wear rate and ability to absorb impact loads in rough conditions.

The cushion is generated by a lift system, in which fans pump air from atmosphere into the plenum beneath the craft and usually into the seals, particularly the stern seal which has to be inflated to a higher pressure than in the cushion. The fans are normally of a standard centrifugal type as used in ventilation systems. The airflow rate should be sufficient to fill the cushion volume in a time of between 5 to 10 seconds, depending upon the craft size. The lift system is normally powered separately from the propulsion system, but a few designs have integrated lift/propulsion machinery systems.

A1.2.3.2 Stability requirements

Designers should appreciate that the cushion generates a de-stabilizing influence on the stability of SES, particularly in roll. Only one incidence of overturning has ever occurred, and that was on an experimental craft (reference 2).

The subject of SES overturning has since been thoroughly investigated and standards have been proposed (reference 3), particularly with regard to operations in beam seas and their effect on overturning boundaries with respect to hullform and height of the vertical centre of gravity (reference 4).

Roll stability considerations dominate the selection of the cross-sectional form of SES. Such stability is primarily generated by the width of the sidehulls and their separation; ie. the cushion beam. As a very generalised rule the minimum cushion beam (Bc) for a particular design should exceed:

$$Bc = ((Vcg^2)/Bs) - (2 \cdot Bs)$$

where Vcg is the vertical centre of gravity (from keel) and Bs is the average width of the sidehull

The pitch stability of SES is also controlled by hull buoyancy forces, but also importantly by restoring moments generated by the seals, contributing up to 30% of the total moment. In high speed operations water drag on the bow seal can, under some circumstances buildup quickly, causing the craft to trim down and rapidly decelerate (reference 5).

A1.2.3.3 Operating speed range

Due to their low resistance characteristics at high speed (see section A1.2.5.1), SES tend to be selected for operations which require a dash capability at speeds in excess of 40 knots, ie. Froude numbers in excess of 1 .O. Experimental craft have reached speeds of 92 knots (reference 5) and higher speeds would be possible with suitable propulsor development.

At lower speeds the resistance curves are characterised by humps and hollows which tend to be more pronounced than those for displacement craft. In particular, the main hump occurs at a Froude number of around 0.75 although this varies slightly with length/beam ratio and a second hump occurs at close to 0.3. For a 50m long craft these Froude numbers equate to speeds of 32 and 13 knots respectively. For lower speed requirements such as MCM roles, the designer should be careful to select a craft with a suitable length which avoids operating too close to the humps.

It is of course possible to operate at low speeds with the lift system stopped and the craft boating like a catamaran. For prolonged hullborne operations the seals should be retracted by some mechanical means against the underside of the wetdeck in order to reduce craft resistance. The possibility of damaging the seals if they are not retracted, due to water collecting in the hags and overloading them, should be recognized.

The hullborne resistance at speeds below a Froude number of 0.4 is likely to he less than that when cushionborne. However, such operations invalidate the cushionborne attributes of low signatures and improved shock hardness.

A 1 . 2 . 4 Layout Arrangements

A.1.2.4.1 Accommodation

Due to their relatively wide beam in comparison with monohulls of similar length, the layout of the accommodation spaces on SES can be conveniently arranged on one or more decks as required, bearing in mind the importance of the vertical CG height on stability (section A1.2.3.2).

The selected arrangements should reflect the need to position noise sensitive areas away from local machinery spaces. Onboard motions tend to increase towards the bow and hence these are less comfortable areas. In head seas, minimum vertical motions occur about 33% of the length from the stem.

Al.2.4.2 Deck Space

As above, deck spaces can normally be arranged as desired. Aft deck layouts are normally preferred for helicopter operations and deployment of overboard equipment (such as MCM gear). The high freeboard when cushionborne sometimes necessitates the use of stem flats below the main deck. Side decks are often not used in preference to internal passageways.

Considerable spray tends to be generated from the air cushion, and particularly at low speeds. This can make working on open decks uncomfortable. However, there are ways of suppressing the spray by use of external skirts, which can be made to drape over the seals.

A1.2.4.3 Machinery

The sidehulls should be made sufficiently wide to contain the main propulsion machinery, although often the hulls have to be bulged on their inboard sides. The arrangements are normally paired (ie. half the machinery in each hull) for convenience and to improve survivability.

The lift system can usually be situated on the main deck with air from the main lift fins ducted through into the forward part of the cushion. Additional fan systems are required for bag type seals at the stem and possibly forward, or as cushion divider seals. Fan systems are normally installed on the main deck or in the upper portion of the sidehulls.

Separate lift engines are usually installed, although a combined propulsion/lift powering arrangement can sometimes be employed.

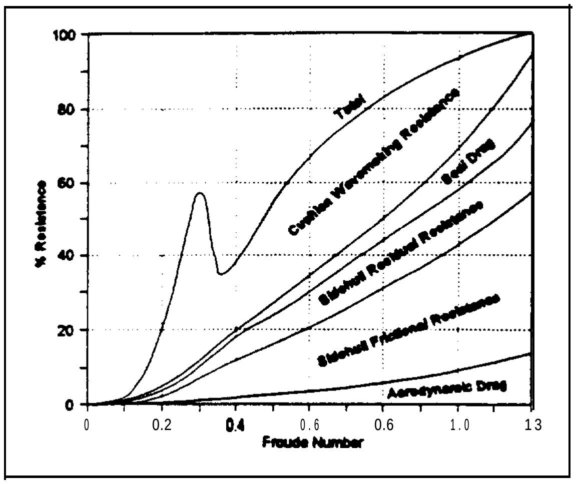
Alternatively, for multi-role applications the lift engine could be clutched into the propulsor gearing in order to provide a low speed boating capability. Higher powered main engines would be reserved for the dash speed with the lift system reconnected.

A 1 . 2 . 5 Resistance and Powering

A1.2.5.1 Resistance Components

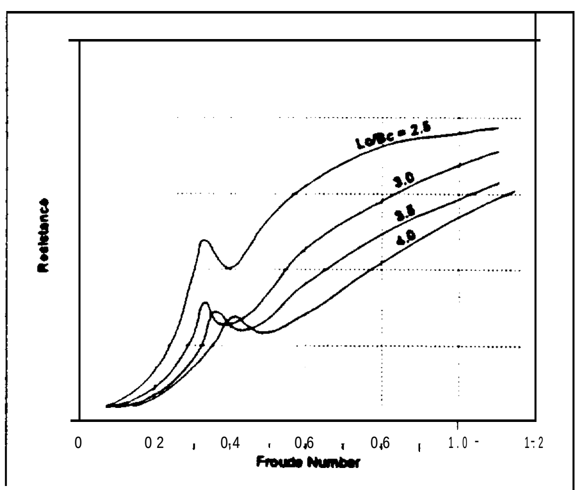
The resistance of SES is complicated by the presence of the air cushion which generates waves and at low speed is a major source of drag. The designer should appreciate that the shallow, wide “barge-like” cushion depression can cause a higher wavemaking resistance at Froude numbers close to the humps (0.3 and 0.7), than normal displacement craft. This feature is particularly important in MCM applications.

At higher **Froude** numbers (> 1.0) cushion wavemaking reduces and **sidehull** frictional resistance (and to a lesser extent residual resistance) become dominant, as shown in figure A1.2.3. The resistance caused by the seal drag and that due to aerodynamic effects should not be forgotten. The estimation of all components is now well understood and is predictable with acceptable accuracy (reference 6).



FigureA1.2.3
Calm Water Resistance Components

The influence of cushion length/beam ratio has a significant effect **on the** total resistance, as shown in figure A1.2.4. In this example the higher cushion length/beam ratio craft showed advantage, but in practice the situation will **vary** depending upon the selected **hullform and the** cushion loading.



FigureA1.2.4
Effect on **Resistance of Change in L/B Ratio**

A1.2.5.2 Overwave Resistance and Speed Loss

The added resistance of SES in waves is **particularly noticeable in** long crested head seas (as typically seen in **a** towing tank) where cushion wave pumping **increases** the air flow **loss which reduces** time • **average cushion pressure, increases** the average draught and therefore the wetting resistance of **sidehull** and seals which contribute to a significant involuntary speed loss similar in magnitude to the voluntary speed loss required by most other craft for an acceptable ride. For example, a **50m** craft **designed** for 50 knots in calm water might be expected to lose up to 20 knots when operating into 3m long crested head seas (reference 6).

On other headings the added resistance and corresponding speed losses are significantly less, as might be expected.

A1.2.5.3 Propulsion

With their shallow draught SES have inherent difficulties in achieving high propulsor efficiencies. Surface piercing, controllable pitch propellers have been fitted to SES, but waterjet propulsion is more usually employed. The design of the waterjet inlet and ensuring its proper immersion, are crucial factors in such installations. High efficiencies are often claimed by manufactures, but designers should be aware that overall propulsive coefficients rarely exceed 0.65.

Propulsion using more conventional type propellers which need shallow draught, is feasible for speeds below 35 knots and for low speed applications is probably more efficient. However, radiated noise levels are likely to be higher and low draught requirements may necessitate the use of smaller diameter propellers with reduced efficiencies.

The total power requirement of SES has to include that for both propulsion and lift systems. At high speed the lift system will require about 15% of the total installed power, although this can be reduced slightly for low speed operations (ie. MCM). The variation in total installed power with Froude number is indicated in figure A1.2.5. The trend line should be regarded as approximate since it is based on only a few craft types and the all-up-weight of many commercial craft is not released. In general terms the increase with Froude number can be seen to be almost linear.

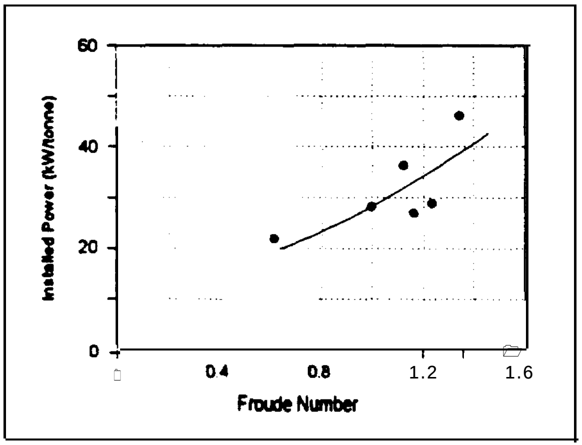


Figure A1.2.5
Typical Installed Power Requirements of SES

In overwave operation, the possibility of aeration of the waterjet inlet (usually referred to as broaching) is of concern. This causes overspeeding and torque surges in the propulsion transmission system and can lead to failures. The remedy is to slightly reduce the lift fan setting, which will lower the cushion pressure and increase the hug immersion. A small aft movement (of about 2% of the length) of the longitudinal CG position also helps by trimming the craft by the stern.

A1.2.6 Seakeeping

A1.2.6.1 Motions in a Seaway

Perhaps rather surprisingly, it has been found that the supporting air cushion does little to damp the motions of SES. In fact at high speeds in low sea states, resonance in the air cushion due to flow variations and stern seal "bounce", can result in a hard "cobblestoning" type ride. This can be greatly alleviated by ride control systems which damp the pressure pulses by venting cushion air to atmosphere, although such systems are rather wasteful in energy terms.

In rougher seas simple venting devices have little effect on pitch, roll and heave motions which are similar in magnitude to those of equivalent sized catamarans. Such motions are generally tolerable in wave heights up to about 60% of the cushion depth. In such seas, operating into-sea where motions tend to be most severe, pitching of about 2 deg (standard deviation) should be expected with vertical accelerations of around 0.12g (tms) at amidships.

The above levels refer to full power operations. Slowing down will give a noticeable reduction in acceleration levels but may not reduce pitching, since it is possible that the wave encounter frequency will become closer to that of the craft's natural pitching frequency (see reference 7). Research into more sophisticated ride control systems able to reduce pitching by cushion subdivision, is being carried out by various authorities (eg. reference 8).

Motion levels can be predicted by computer simulation programs to a reasonable level of reliability (reference 9). In general, changes to the cushion pressure and planform, and the slenderness of the sidehulls all appear to have secondary influences on the motions of a given design. It has been found that in some circumstances reducing the pressure in the stem seal has a more powerful influence.
The subject is therefore one of continuing development, but in general the designer should appreciate that the seakeeping of SES is an area of concern. The subject has been reviewed in reference 10.

A1.2.6.2 Slamming and Wetness

Although the amplitude of motions can be significant as explained above, the increase in undercraft clearance provided by the SES cushion generally results in less slamming and deck wetness than can occur on catamarans in rough seas.

Provided that the wave height is less than the cushion depth, serious wetdeck slamming is unlikely to occur and the hulls are usually too narrow to generate high keel loads. The bow seal is normally able to provide sufficient restoring moment in rough head seas, to lift the bow and prevent green seas coming on deck.

A1.2.7 Structures

A1.2.7.1 Seals

The rubberised fabric seals fitted to SES are a relatively new technology and have been successfully developed for craft up to about 30m in length. In general full depth finger type seals have been used at the bow and double-loop bag seals at the stern, as illustrated in figure A1.2.6. Variations on these designs have been trial, but in general have suffered from strength defects.

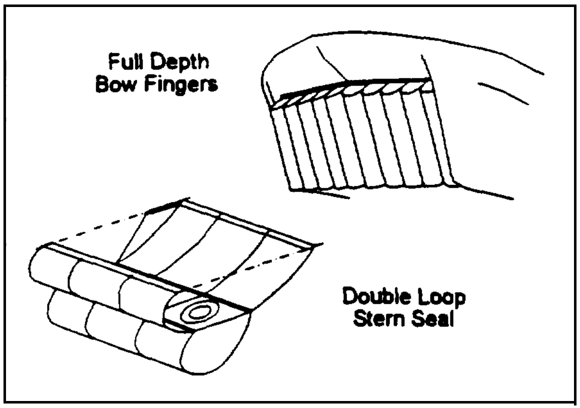


Figure A1.2.6
Seals on Existing Craft Types

If properly designed and manufactured seals should not suffer from wave damage. Stem seals should last for many thousands of operations hours. Bow seals tend to wear more at their tips and may need to be replaced every 500 operational hours, but this is somewhat dependent upon craft speed. In lower speed (less than 25 knots) applications, the tips can be replaced (reference 11) extending the finger life to several thousand hours.

The extrapolation of seal technology to larger craft has been investigated and is probably well defined up to craft of 60m in length. For such sixes other types of seals have been considered. Bag plus finger types are preferred at the bow and triple-loop types at the stem, figure A1.2.7.

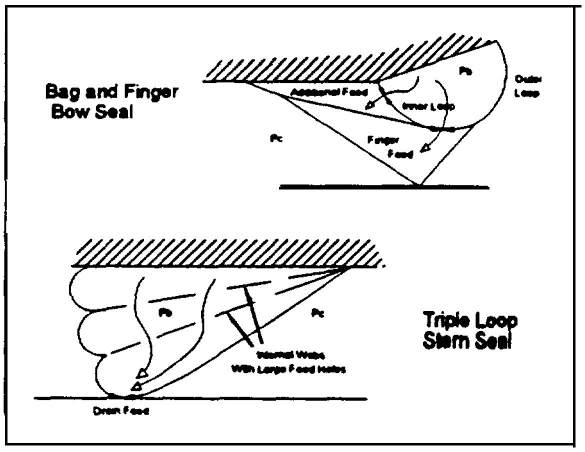


Figure A1.2.7
Seals on Larger Craft

Beyond the 60m craft size, there is much more uncertainty in seal design especially for high speed applications. There is also a lack of suitable heavier weight materials, and this may limit the development of large SES. New materials may become available, but will need to he produced in reasonable mass-production in order to justify development costs.

A1.2.7.2 Structural Design

The designer should aim to minimize the weight of SES in order to facilitate high speed performance. Structure weight can he reduced by careful design and choice of material, but these options depend upon a correct understanding of the design loads.

The database available from existing designs is growing steadily and loads are now normally based on Classification Society Rules (eg. reference 12). However, these rarely produce the most efficient light-weight structures, and designing from first principles is usually recommended for the development of optimum structures (reference 13). Tests using "grillage" segmented type models may need to be conducted, in order to better define the longitudinal and transverse loads.

High speed impact loading is clearly of concern, but perhaps somewhat surprisingly the greatest structural loads are often generated in the event that the craft becomes hullborne at low speed in rough seas. In this case longitudinal bending and torsional loads can dictate the form of the structure, particularly in the case of larger craft.

A1.2.7.3 Local strength

The local strength in secondary structure needs to be considered particularly of the forward crossdeck ramp with regards to the possibility of slamming (although see Al .2.6.2). High loads can also be generated in this structure and in the aft cross-deck, by drag forces on the seals in rough conditions. Possibly the worst case is again with the craft hullborne and the seals partly filled with sloshing water.

The results from underwater explosion "shock" trials, indicate that stress concentrations tend to occur in the structure along the upper longitudinal comers of the cushion compartment. The addition of a suitable radius to the structure joint in this area should be considered.

A1.2.8 Weights

A1.2.8.1 Use of Lightweight Materials

Powering considerations dictate the use of lightweight materials in the construction of SES, since the cushion pressure is directly related to the operating weight. Most commercial craft are built in GRP laminate or foam sandwich structures, and these have proved to be generally reliable and cost effective. The materials also have high sound absorption properties and no magnetic signature and therefore offer advantages for military applications.

The weight of lightweight structures depends upon the particular application, but for general design purposes an overall hull density of about $40 kg/m^3$ can be assumed. This together with the use of high-speed diesel or gas turbine machinery installations, results in SES being able to achieve large payload fractions of between 20 to 2596 of the craft's all-up-weight.

A1.2.8.2 Effect of Weight on Performance

As might be expected, changes in craft weight influence the high speeds achievable by SES. As an approximate rule, small changes in operating weight will proportionally change the speed (ie. a 10% increase in weight will cause about a 10% speed loss).

Designers should also understand that the longitudinal position of the centre of gravity should be maintained slightly aft of the centre of the cushion (about -1% of cushion length is normal). This will result in an optimum running trim in calm water. Any changes in weight will therefore need to be accompanied by a rebalancing of the longitudinal CG, which is usually achieved by a fuel ballasting system.

Al.2.9 Survivability

Survivability consists of both susceptibility and vulnerability.

A1.2.9.1 Susceptibility

In terms of susceptibility the SES has potential advantages over displacement craft as the cushion reduces contact with the water, raises potential noise and magnetic sources and so lowers underwater signature.

A1.2.9.2 Vulnerability

With regard to damaged stability SES are likely to be able to maintain a high level of survivability. The hull is mainly out of the water or probably can be raised out by operating the lift system. The machinery is normally paired in the sidehulls and one side is likely to remain operable after side damage to the opposite side. Shock teats have demonstrated the SES resistance to underwater damage and the ability of the seals to withstand substantial overpressures.

A1.2.10 State of the technology

About 200 SES have been built and by far the majority are in commercial service in various countries worldwide. Their lengths are generally less than 30m, although a 51m test craft (French AGNES 200) and a 55m MCM craft (Norwegian Oksoy class) have recently been built. In general it can be said that these craft are operated successfully and many have been in service for over ten years.

The state of technology in respect of design procedures is therefore well established for craft of this size range. Both performance and seakeeping characteristics can be predicted with reasonable confidence.

Construction techniques are also well developed and much has been learnt on the use of GRP lightweight structures and rubberised fabric seals. Production methods can therefore be said to be well established.

A1.2.11 Overall Advantages and Disadvantages

SES have without doubt a significant speed advantage over most other forms of unconventional craft (except ACV's), due to their low resistance. However, at low speeds their resistance can be higher than similar sized monohulls. The speed loss in head seas can also be significant.

SES have potential advantages compared to monohulls in MCM roles, due to their lower underwater signatures and better shock resistance.

In more general terms the shallow draught of SES may be considered an advantage compared to monohulls. Their freeboards are relatively high which can cause difficulties in handling equipment. However, the SES is able to control its height by adjustment of the cushion pressure. This control also means that the craft may be better able to cope with hull damage.

It should generally be recognized that SES cost more to build and, due to added complexity, more to maintain than monohulls.

A1.2.12 Concluding Remarks

In the foregoing paragraphs an attempt has been made to give general design advice on the various aspects of SES technology. Generalised statements and tentative guidance rules have been offered to allow the designer to appreciate the task of the concept design of such craft.

Clearly this subject is difficult to cover adequately in a document of this size, since the technologies have been extensively researched and developed over the past years. 'The designer is encouraged to further study the references to this work and in turn those cross-referenced, in his search for detailed advice,

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Al.3 SWATH

A1.3.1 Introduction

This document offers guidance on the procedures and techniques for the concept or preliminary design of SWATH types of un-conventional vessels. The review gives overviews of the hullform and layout arrangements, describes the performance and seakeeping characteristics and comments on the structural requirements and vessel weights.

The review places emphasis on military design requirements and the roles likely to be undertaken by SWATH vessels. A general appraisal of likely operational advantages is given, together with information on the present day state of technology, although this is mainly based on commercial operations.

A1.3.2 General Description

Small Waterplane Twin-Hulled (SWATH) vessels have deeply immersed catamaran type hulls which buoyantly support the craft, but which are greatly reduced in width around the waterline. A typical arrangement is shown in figure Al .3.1.

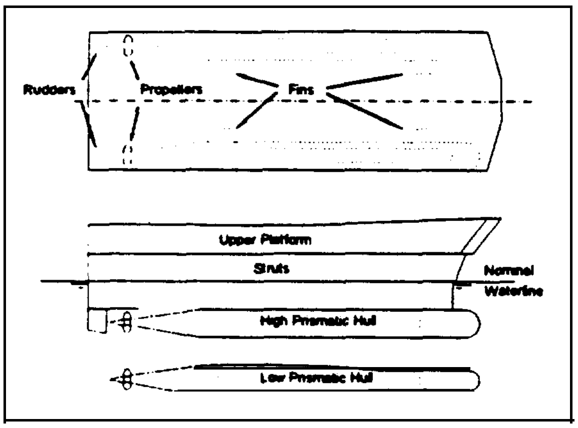

Figure A1.3.1
Typical Arrangement **of** SWATH Vessels

The reduction in waterplane ares gives SWATH vessels the following outstanding features:

- Improved motion characteristics in waves compared to conventional monohulls of similar displacement.
- A small speed loss in waves.
- large deck area for the operation of helicopters.
- Improved propeller performance and sonar operations due to deep submergence.

The selection of hullform has an important influence on the behaviour of SWATH vessels and the control of their operational weight is more critical than for other vessels.

SWATH vessels have been built for open ocean surveillance roles where their improved seakeeping compared to monohulls is of importance. Smaller types have also been considered for coastal patrol and law enforcement duties, as well as MCM route surveillance.

A1.3.3 Fundamental Features

A1.3.3.1 Hullform

The SWATH hullform is characterised by two streamlined submerged hulls, connected to an above water bridging structure by surface piercing struts, narrow in width and with a corresponding small waterplane area. The historical development of SWATH vessels was reviewed in reference 1, and the current state-of-the-art in reference 2.

The submerged hulls are usually circular or oval in cross-section with tapered ends. However, these cross-sections necessitate sharp fairings between the hulls and the struts. A teardrop form is sometimes used which smooths the intersection whilst retaining good hydrodynamic properties, figure A1.3.2.

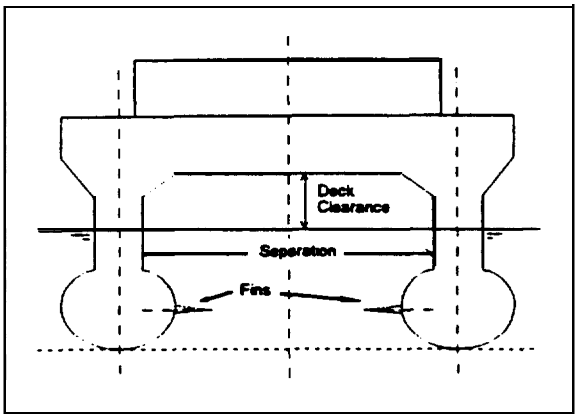

Figure Al .3.2
Typical SWATH Cross Section

The struts are normally continuous along the hull length but in some designs have been split into several sections since single struts tend to increase directional stahility, making the vessel more difficult to turn. However, the resistance of multi-strut configurations can be higher due to interference effects.

Research into the motions of SWATH vessels, has shown that the most important features of the hullform are the size of the waterplane area and the longitudinal metacentric height. Fins are usually added along the inboard sides of the hulls to dampen heave, pitch and roll and improve plane control. These can either be fixed or controllable types, for reasons mentioned in section Al.3.3.2 aft mounted fins are usually fitted to provide trim stability.

Wet deck clearance should be selected to assure acceptable slamming characteristics in the design specification sea state. Reference 4 contains guidance on wet deck clearance heights derived from existing designs. The separation of the hulls needs to be adequate to provide the necessary roll stability in relation to their waterplane area and vertical centre of gravity.

A1.3.3.2 Stability Requirements

The reduction in waterplane area greatly reduces the wave exciting force on the vessel, reduces the heave and pitch restoring forces generated by the struts, and increases the natural periods of heave, pitch and roll. SWATH vessels encounter peak motions in seas with long modal periods. Fins are usually fitted to the inside of the hulls to minimise resonant motions in these conditions. Fins may be actively controlled to further reduce motions.

Designers should be aware that increasing speed causes changes to the distribution of pressure along the hulls resulting in decreased calm water pitch stability. Large trim angles can result at high speeds which reduce cross structure clearance at the bow or stem. These effects can be eliminated by selection of proper fin area and fin area distribution. Fuel and ballast systems can also be designed to counter trim effects.

Due to the reduced waterplane area, the change of immersion with weight is much greater (typically four times) than that of a **monohull** of similar displacement. This characteristic combined with the probability of damage being limited to one of the hulls may lead to high heel angles after damage. In severe cases, these effects have to be compensated by counter flooding of the opposite hull. Suitable tanks or void spaces should be provided for such emergencies. Due to the pairing of machinery arrangements in the side hulls SWATH vessels are likely to remain operable after damage, providing that suitable compartmentation is arranged.

A1.3.3.3 Operating Speed Range

SWATH vessels have higher wetted areas than monohulls of similar displacements, with a corresponding increase in frictional resistance. This tends to limit their speed to Froude numbers of less than about 0.8. For this reason most of the vessels that have been built have maximum speeds lower than 25 knots.

Distinct humps and hollows may appear in the speed - power curve due to strong wave making interference effects (see section **A1.3.5.1).** Major humps occur at Froude numbers of about 0.3 and around OS.

A1.3.4 Layout arrangements

Al.3.4.1 Accommodation

The wide beam of SWATH vessels and the fact that motion levels vary little over the vessel's length, permits the accommodation layout to be positioned on the main deck and on above decks, in a manner convenient to the designer. Since the main engines are often located on the main deck, noise levels need to be considered.

Al.3.4.2 Deck Space

Deck space is not normally limited and wide side and across decks are possible. Helicopter operations can be sited at either end of the vessel which may improve aircraft operability in strong wind conditions. Adequate space can be arranged aft for the deployment of over-board equipment, although the freeboard is often high and movement of large loads can cause trim changes.

A1.3.4.3 Machinery

Due to the narrow width of the struts, it is normally difficult to position the main propulsion machinery in the hulls. Various ways of overcoming this problem have been devised. The use of inclined or **right-**angled drive shafts from engines located on the main deck is an obvious solution for smaller vessels, but power transmission losses and the cost of extra gearboxes discourages such arrangements.

Medium **sized** SWATH vessels have been built using diesel-electric drive systems, but such arrangements tend to be heavy and expensive. Gas **turbine-electric** drives are attractive for larger vessels. Radiated noise can be reduced by the use of electric drive systems combined with generators located above the waterline.

A1.3.5 Resistance and Powering

A1.3.5.1 Resistance Components

At low speeds with Froude numbers below 0.5, the twin hulls and struts of SWATH vessels produce complex wave patterns which both interact and interfere with each other. The resistance effects can usually be predicted with potential flow theory, but should be validated by **model tests.**

The situation **is** illustrated in figure A1.3.3, where the residuary resistance of two forms is compared. The magnitude of the humps and hollows in the curves are dependent upon the distribution of hull volume. The low speed type has a low prismatic **form** (ie. streamlined ends) and the high speed type a more cylindrical high prismatic form. Both forms show minimum residuary resistance at about 0.35 Froude number, indicating a convenient operating speed regime.

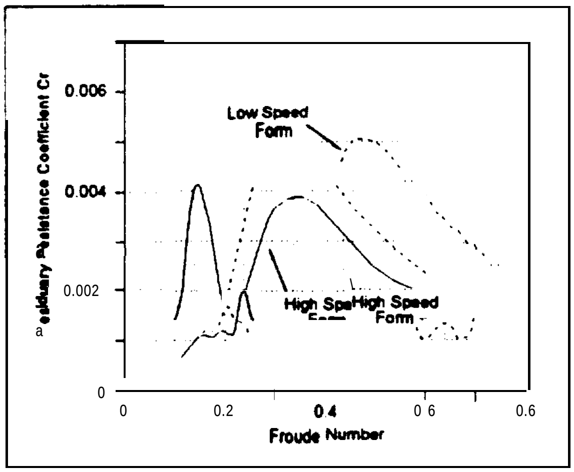

Figure A1.3.3
Variation in Residuary Resistance

At higher speeds frictional resistance becomes significant and since the wetted area of SWATH vessels is appreciably higher than for similar **sized monohulls** (by as much as **60%),** this tends to determine their limiting speed. A typical resistance **breakdown** is shown in figure A1.3.4. In comparison to the main components the resistance of appendages, such as **fins,** is small.

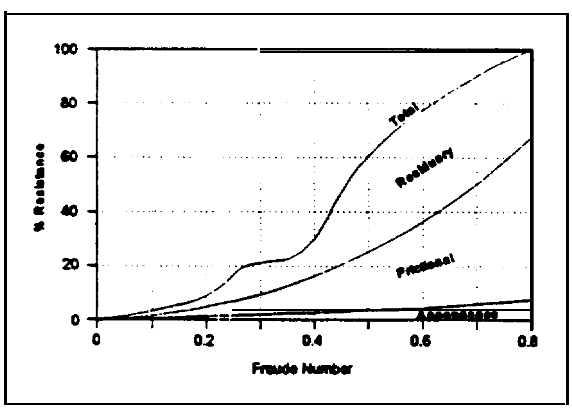

Figure A1.3.4
Calm Water Resistance Components

A1.3.5.2 Overwave Resistance and Speed Loss

The **reduced** motions of SWATH vessels **(see A1.3.6.** 1) result in less added resistance in waves than is typical for monohulls and a smaller speed loss. For example, a **50m** long SWATH designed for **25** knots should be expected to lose **no** more than 2 **knots** in a 3m head sea and less on other headings. Voluntary speed reductions due to slamming, deck wetness, propeller broaching and adverse ship motions are reduced compared to monohulls as well. Both the increase in hull immersion and the reduction in motion, reduce propeller cavitation and the liilii of ventilation. It is possible for the sustained speed in waves to be more than that of a **monohull** with a higher design speed in calm water.

A1.353 Propulsion

Designers should note that the deep draught of SWATH vessels, improved inflow conditions over the after hull and an ability to accommodate larger slower rewing propellers, contribute to an improvement in propulsive efficiency compared to that achieved by monohulls. Overall propulsive coefficients of up to 0.85 have been achieved. Improved propeller cavitation onset speeds are possible with lower radiated noise levels.

The installed power requirements of SWATH vessels varies considerably with Froude number, since the higher **speed** forms require proportionally more power due to their increased frictional resistance. **The** trend is indicated in figure A1.3.5, based on data in reference 2, although this should be considered approximate.

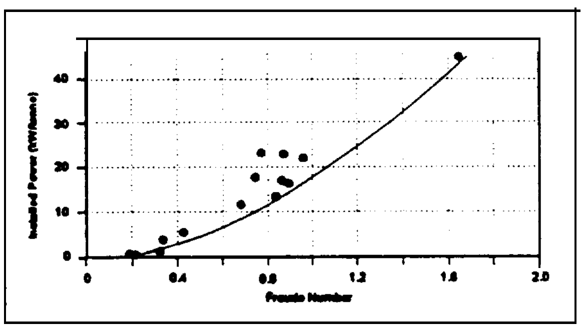

Figure A1.3.5
Typical Installed Power of SWATH Vessels

A1.36 Seakeeping

A1.3.6.1 Motions in a Seaway

The designer should normally be able to ensure that the natural periods of the pitch and roll motions of a particular SWATH **vessel** are **significantly** longer than those **likely** to be encountered in the specification sea **state.** The corresponding motions will therefore be low with low accelerations.

It is not really possible to generalize on the magnitude of the motions to be expected, except to state that in the design sea state pitching should be less than 1 degree (standard deviation) and vertical acceleration levels leas than 0. lg **(rms).**

In **examining the** natural motion periods, care needs to be taken to avoid periods that are close to multiples of those of the waves and to decouple pitch and **roll** periods which can cause corkscrewing in quartering seas. Heave periods tend to be shorter than pitch and roll periods and are more likely to be a cause of resonance.

For higher speed vessels the addition of fin systems is normal as explained in section A1.3.3.2. Active control of such fins will substantially reduce motions and further improve seakeeping characteristics.

Theoretical methods are sufficiently accurate to predict the motions of SWATH vessels (eg. reference 3), but designers need to exercise care in modelling viscous damping terms. These cause greater interactive effects than they do for monohulls.

In general it may be claimed that the seakeeping characteristics of a properly designed SWATH vessel will be superior to monohulls several times greater in displacement. The reduction in motions improve habitability and extend helicopter operations.

A1.3.6.2 Slamming and Wetness

Unappended SWATH hulls are lightly damped in heave. Heave resonance can occur in waves with periods near the vessel's heave natural period. Severe wet deck slamming can result. Heave response near resonance can be dampened, and the related wet deck slamming greatly reduced, by the addition of horizontal fins to the hulls. Active control of these fins can significantly alter motions to further reduce slamming. Vertical acceleration levels will increase slightly as a result.

Slamming on the wet deck and sides of the struts can also result from normal ship operation in rough seas. Appropriate secondary loads for the design of shell structure must be used.

Deck wetness is rarely a problem due to the high freeboard.

A1.3.7 Structures

A1.3.7.1 Structural Design

The specialised hullforms of SWATH vessels demand careful design consideration. Only one Classification Society (reference 4) has issued guidelines on the primary and secondary loads to be expected in the structure. The designer should therefore expect to have to partly rely on a first principles approach.

The main concern of the designer is with side loads acting on the hulls and struts, and the transverse bending moments and shear forces these generate in the crossdeck structure, reference 5. Such loads tend to be greatest when operating at very low speeds in beam seas, particularly in turns, and tend to be greater for single strut forms than for twin strut types. The high loads in the connections between cross deck and side hulls can lead to fatigue problems.

Reference 6 provides information on primary and slam load estimating relationships over a wide range of ship sixes.

Grounding loads should not be overlooked, since large torsional stresses can be generated if the hulls are supported at diagonal corners. An overall review of the structural loading of SWATH vessels was given in references 5 and 6.

Several methods are available for the structural design of SWATH vessels using finite element analysis (eg. reference 7). The designer should anticipate fatigue in the hull/strut and strut/cross-deck joints.

A1.3.7.2 Local strength

The possibility of slamming in extreme conditions (A1.3.6.2) will be of concern to the designer with regard to the strength of the crossdeck structure. Layouts normally dictate that the angle between the crossdeck structure and the water surface will be small. This promotes the generation of significant slamming pressures, which are difficult to absorb.

Loads induced by the fins should also be considered. These will tend to be greatest when operating at high speeds in rough seas. Hydrodynamic and inertial loads resulting from large motions at zero speed may be dominant.

A1.3.8 Weights

A1.3.8.1 Weight Control

Due to their small waterplane area, the draught and hence under-deck clearance of SWATH vessels is particularly sensitive to weight changes. Weight control during build is especially important and weight growth in service can cause difficulties. Weight control is normally catered for by the use of sea water ballasting systems, although additional bulges can be added to the hulls if growth is considerable.

Vessels of less than 30m have been built in aluminium alloy, but steel (maybe high tensile strength) is required for larger vessels in order to cope with the structural loads (see A1.3.7.1). An overall hull structural density of 50-90 kg/m' for aluminium alloy and 95-130 kg/m for steel, can be achieved depending on configuration and design requirements. Typical payload weight fractions achieved are between 10 and 15% of the vessel's displacement.

A1.3.8.2 Effect of Weight on Performance

As mentioned above, operating weight is usually held constant by the use of ballasting systems. The designer should remember that it is important to maintain the longitudinal CG close to the centre of buoyancy, in order to avoid trim difficulties. Tankage design should reflect the weight distribution of the ship in all loading conditions. Sufficient flexibility in ballasting capability should be provided to compensate for changes in loading due to environmental effects such as topside icing. Fluid system capabilities should be adequate to provide required trim control.

A1.3.9 Survivability

Survivability consists of both susceptibility and vulnerablity .

A1.3.9.1 Susceptibility

Underwater signatures are favoured by the ability to mount equipment on the cross deck. The large efficient propellers also help to keep noise down, however the need to locate propulsion machinery in the side hulls can create problems.

A1.3.9.2 Vulnerability

Although tbe large cross deck ensures excellent ultimate stability, provided sufficient watertight subdivision is incorporated, list angles can be large making continued operation very difficult.

A1.3.10 State of the Technology

Small numbers of SWATH vessels have been produced over the last 15 years, and some 20 different designs are now at-sea. Most of these vessels are about 20-30m in length. Two classes of 60m patrol ships (T-A GOS, JOS), a 60m oceanographic research ship and a 116m cruise ship (Radisson Diamond) have also been built. The majority of the designs are of Japanese or US origin. These countries lead in SWATH development.

Much research has been conducted into prediction of resistance, powering, motions and loads, and the state of technology can be said to be well advanced. Sea trials have demonstrated that performance can be predicted well.

Fabrication techniques are less well established since only one yard (Mitsui) has produced a number of different types of SWATH vessels. There appear to be more complications in building a SWATH type than a conventional monohull of similar displacement. However, experienced builders of catamaran type vessels should not encounter any major problems.

The requirement to more strictly control weight during build was mentioned in A1.3.8.1. Construction techniques will need to be more firmly established before SWATH vessels can be expected to be built on-time and at-cost.

A1.3.11 **Overall Advantages and Disadvantages**

SWATH vessels have without doubt, improved seakeeping abilities compared to other types of unconventional craft. They have also demonstrated superior seakeeping than similar sized monohulls, but their greater wetted areas generally result in higher resistance levels and installed power requirements, For this reason the maximum speed of SWATH vessels is usually lower than 25 knots.

The small waterplane area makes the craft very sensitive to displacement changes and to trim.

In more general terms the draught of large SWATH vessels may affect their ability to use existing port facilities. They also have relatively high freeboards, which may cause difficulties in handling equipment.

It should generally be recognized that SWATH vessels cost more to build and slightly more to maintain than similar sized monohulls.

A1.3.12 **Concluding Remarks**

In the foregoing paragraphs an attempt has been made to give general design advice on the various aspects of SWATH vessel technology. Generalised statements and tentative guidance rules have been offered to allow the designer to appreciate the task of the concept design of such vessels.

Clearly this subject is difficult to cover adequately in a document of this size, since the technologies have been extensively researched and developed over the past years. The designer is encouraged to further study the references to this work and in turn those cross-referenced, in his search for detailed advice.

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Al.4 CATAMARAN

A1.4.1 Introduction

This document offers some guidance on the overall characteristics of catamarans, with particular reference to military applications.

A1.4.2 General Description

A catamaran is a vessel with the hull composed of two different bodies, usually called demi-hulls, connected by an above water cross-deck, figure A1.4.1.

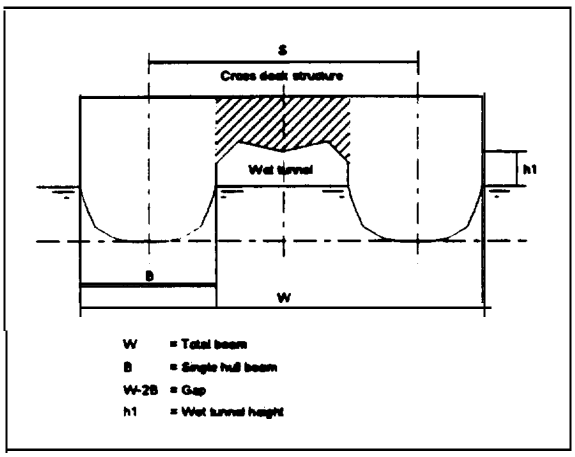

Figure A1.4.1
Catamaran Cross Section

Each demi-hull can be either symmetric or asymmetric, but the entire hull is symmetric about the centre line, ie. each demi-hull is the mirror image of the other. The transverse distance between the two demi-hulls at the water-plane is called the gap, figure A! .4.1. The space located between the two demi-hulls and under the cross-deck is called the wet tunnel.

SWATHs and the SESs are particular types of catamarans, but due to their special features they are usually considered as different types of unconventional craft.

Catamarans can be used in two different field of application:

- Conventional displacement catamarans
  Displacement catamarans have been considered and constructed for the following roles
  - Oceanographic vessels (reference 14 and 15).
  - Hydrographic vessels.
  - Submarine rescue vessels (reference 4).
  - Mine countermeasure vessels (reference 16).
  - Environmental protection vessels for oil spill recovery.

- **Fast catamarans**
  Usually planing or almost-planing hulls, including the wave-piercing hull forms. Fast catamarans have been considered and constructed for the following roles

  Law enforcement.
  Fast personnel transportation.
  special operations.

A 1 . 4 . 3 Fundamental Features

A1.4.3.1 Hull Form

Unlike a monohull each catamaran demi hull does not have to be symmetric about its own centre line. There are thus several form options, figure A1.4.2:

- **Symmetric hulls**
- **Asymmetric (not divided) hulls**
- **Asymmetric (divided) hulls**
- **Partially asymmetric hulls**
  Usually symmetric in the stern and asymmetric in the bow.

These are shown in figure Al .4.2.

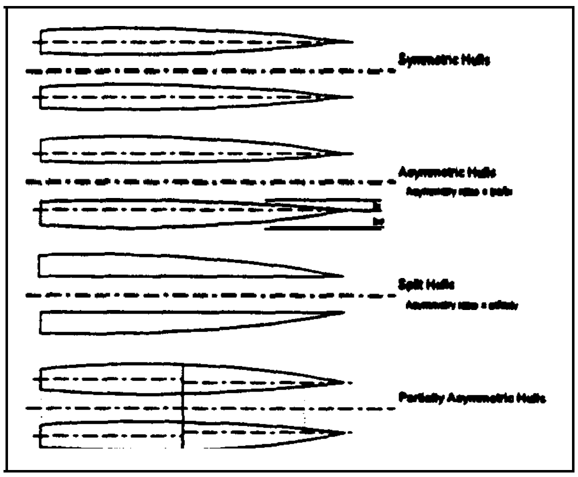

Figure A1.4.2
Catamaran Hull Forms

In the case of asymmetric hulls a parameter known as the degree of asymmetry is defined as the ratio between the external and the internal beam. For divided hulls the degree of **asymmetry is infinite, figure A1.4.2.**

Usually symmetric hulls in isolation have the best **performance** in terms of both resistance and sea-keeping characteristics. However when the two hulls are combined the wake created by one hull reacts with that created by the other and the net effect is generally negative resulting in an increase **in** resistance, tunnel wetness etc. figure A1.4.3. In order to minimise this so-called interference effect it is necessary to reduce the wake created by the internal half of the hull directed to the inside of the vessel, by decreasing the internal half-angle of entrance of the hull. **This** is the main reason for using asymmetric hulls.

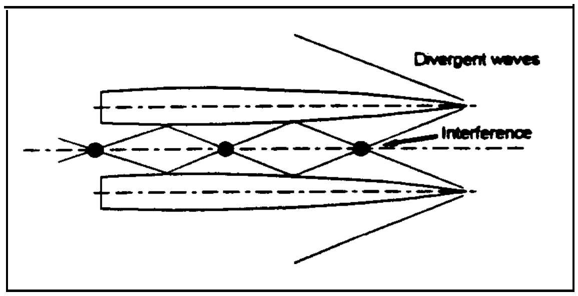

Figure AI.43
Wave Interference Effect

The disadvantages of asymmetric hulls are

- **Increased resistance**
  Over that of the hull in isolation.

- **Poor course-keeping characteristics in a seaway**

- **Increased building costs**
  This is due to the difference between the two hulls. In particular when using GRP construction for asymmetric hulls two different **moulds** are required, while for symmetric hulls only one would be necessary.

The length/beam ratio of each **demi-hull** of a catamaran is not limited by stability requirements, and so very slender forms are possible.

An **important** parameter that characteristics the catamaran hull form is the gap ratio, ie. the ratio between the distance between the two hulls and the length. The gap ratio g is usually calculated as

$$g = (W-2.B)/L$$

Other ratio used **are:**

$$g_1 = (W-B)/L$$

$$g_2 = (W-2.B)/W$$

The g_2 ratio is more intuitive, because it **is the ratio between the** beam of the gap and the total beam, however the g and g, ratios are more directly linked with the geometry of the waves between the two hulls, figure A1.4.3. Reference 7 recommends a **minimum ratio g_2** of **1/3** for fast slender catamarans.

Another important parameter for catamaran hull forms is the height of the wet tunnel, which has an influence on

- Resistance
  This increases sharply when the wake wave crests in the tunnel wet the cross deck.

- **Sea-keeping and structural loads**
  This is because of the possibility of tunnel slamming occurring in rough seas.

Methodologies for the selection of basic hull parameters and for preliminary speed predictions for fast slender catamarans are provided in reference 7.

A1.4.3.2 Stability Requirements

The transverse stability of catamarans is not usually a problem, because of the very large metacentric height and subsequent high initial transverse stability. A study on the behaviour of a small catamaran in breaking waves is provided in reference 23. The damaged stability problem is different from that of a monohull because

- **Asymmetricdamage**
  The most probable and most demanding damage condition is the asymmetric case.

- **Stability margins**
  Stability requirements are usually easily met, because of the very high GM. The more demanding requirements are those concerned with reserve buoyancy ie. the position of the margin line.

Requirements for intact and damaged stability applicable to naval catamarans are provided in reference 9. Requirements for intact and damaged stability applicable to fast commercial catamarans, in particular to fast ferries, are given in references 8, 21 and 22.

A1.4.3.3 Operating Speed Range

As described in section 1.4.2 catamarans can be used in two different speed ranges

- **Conventional displacement catamarans**
  Operating at Froude numbers up to 0.4.

- **Fast catamarans**
  Operating at Froude number from 0.6 to 1 .O.

For higher speeds other types of vessels, such as SES, are usually preferred. As explained later in section 1.4.5.1 the resistance curve is affected by pronounced humps, particularly in the low speed range. It is of course desirable to ensure that both the cruise and top speeds do not coincide with the humps, unfortunately their location and magnitude can only be determined with tank trials.

A1.4.4 Layout Arrangements

A1.4.4.1 Accomodation

The layout of the accommodation spaces on catamarans is relatively free of restrictions because

- Cross deck **structure**
  The wide beam of the cross deck provides more useable deck area than for monohulls of similar length.

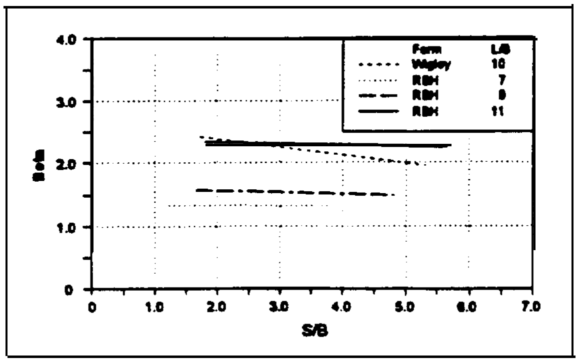

Fig Al.4.6
Variation of **Vii Interference Factor**
B with S/B

The factor t is **very dependent** on the speed, and usually the curve of this factor related to Froude number is **characterised** by the presence of pronounced hollows and humps. It **is** of course desirable that both the cruise and top speeds do not coincide with the humps. Unfortunately the location and magnitude of such humps are **very** sensitive to the gap ratio and the hull form and so tank trials are needed. For some limited speeds the factor can be less than 1 meaning that the effect of the interference is a decrease in the total wave resistance. Indicative illustrations of the variation of the t factor with Froude number for different ratios of S/L are shown in figures A1.4.7, A1.4.8, A1.4.9 and A1.4.10, taken from reference 6. Some guidance on the use of this approach for making a preliminary estimation of the resistance of a catamaran is given in reference 6.

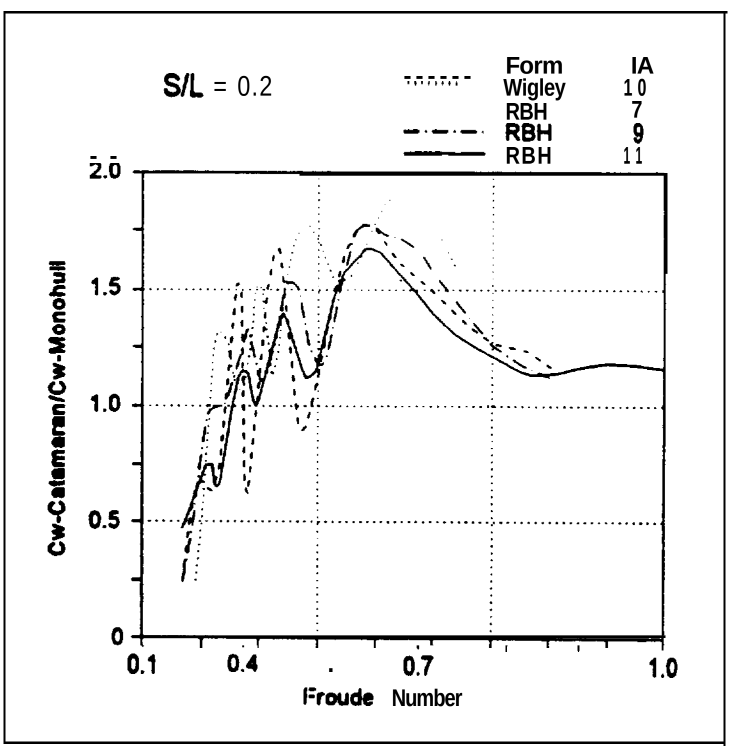

Figure A1.4.7
Wave Resistance Factor, S/L = 0.2

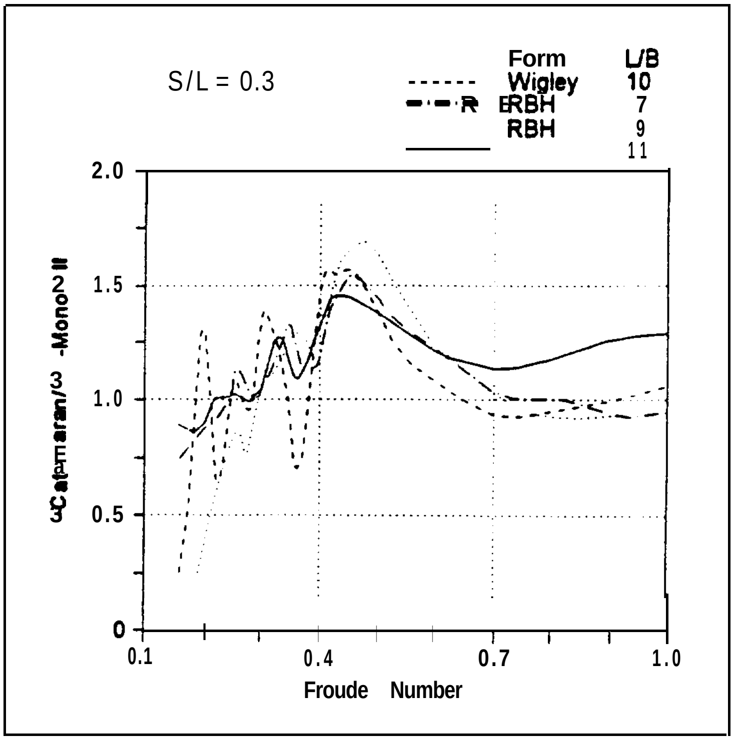

Figure A1.4.8
Wave Resistance Factor, S/L = 0.3

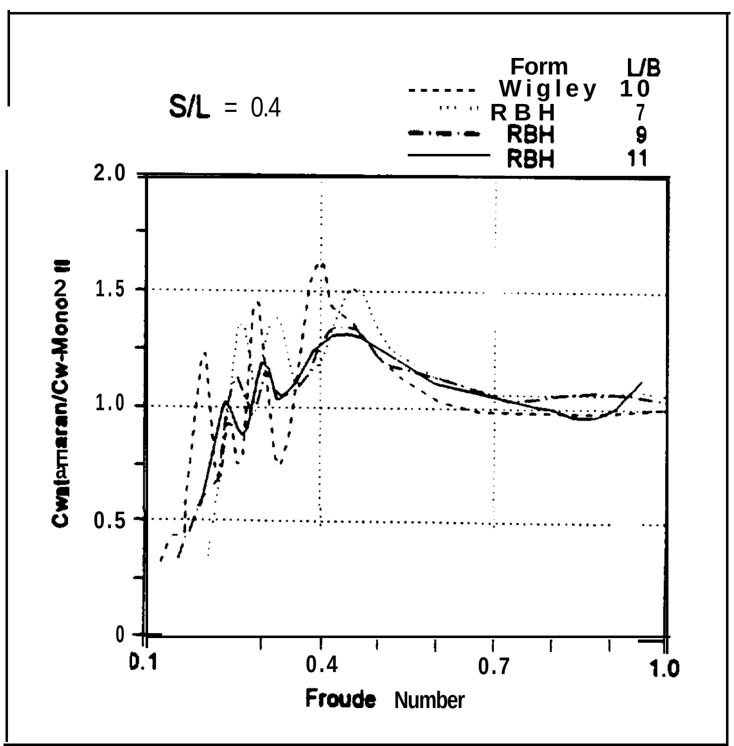

Figure A1.4.9

- VCG **constraints**
  The lack of constraints on the vertical position of the CG allows the fitting of many levels of superstructure.

Due to high pitch and acceleration levels, the bow areas of a catamaran are less comfortable.

Al.4.4.2 Deck Space

Aft deck spaces are normally preferred for the deployment of over-board equipment such as oceanographic and MCM equipment. A particular feature of catamaran craft is the ease of fitting moon pools near the CG. The bow deck is usually less suitable for deck equipment due to the high freeboard and the reduced area. The arrangement of anchors and capstans can be unconventional, figure Al .4.4.

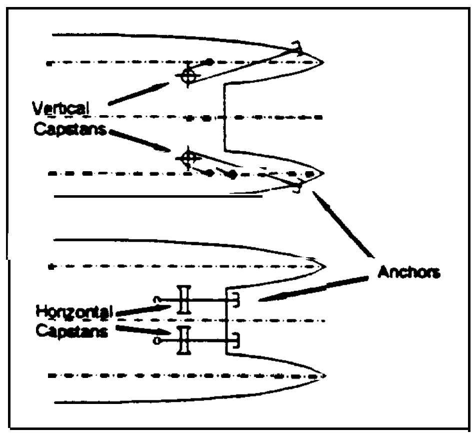

Figure A1.4.4
Catamaran Anchor Arrangements

A1.4.4.3 Machinery

Catamaran engines can be accommodated either inside the hulls or on the deck. Layouts with engines inside the hulls are more common while those with engines on the deck are used when there are very low radiated noise requirements, such as is the case for Mine Counter Measures (MCM) or research vessels, or when the space in the hulls is very restricted.

A1.45 Resistance and Powering

A1.4.5.1 Resistance Components

The resistance components of a catamaran are the same as for a monohull, however the problem is complicated by the inter hull interference, it. the factor by which the resistance of a single demi-hull is multiplied to take account of the presence of the other demi-hull. The interference is principally due to the interaction between the waves of the two demi-hulls that constructively interfere to produce crests, figure A1.4.3, but also because the velocity and the pressure of the water on the internal side of each demi-hull are modified by the presence of the other demi-hull. The way that the interference is dealt with depends on the approach that is adopted for calculating the resistance. The traditional approach using the ITTC 1957 line consider two components

- Frictional **resistance**
  This is proportional to the Reynolds **number.**

- Residual **resistance**
  Calculate as the difference between the total and the **frictional** resistance and scaled according to Froude's law.

The **ITTC** 1978 approach also considers two components

- **Viscous** resistance
  The frictional resistance calculated using the **ITTC** 1957 line, but multiplied by a form factor, (1 + k), evaluated numerically or experimentally.

- Wave **making resistance**
  Calculated by taking the difference **between** the total and the viscous resistance and scaled according to Froude's law.

Following the **ITTC** 1978 approach the resistance coefficient of a catamaran can be expressed as

$$C_{tcat} = (1+b.k).C_f+(1+t).C_w$$

where

C_{tcat}	=	Coefficient of total resistance of the catamaran.
C_f	=	Coefficient of frictional resistance obtained from the **ITTC** 1957 correlation line.
C_w	=	Coefficient of wave resistance for the single demi-hull in isolation.
$(1+k)$	=	Form factor for the single demi-hull in isolation.
b	=	Viscous resistance interference factor, taking account of the pressure field change and of the velocity augmentation between the 2 **demi-hulls.**
$(1+t)$	=	Wave resistance interference factor.

This is shown in figure Al .4.5.

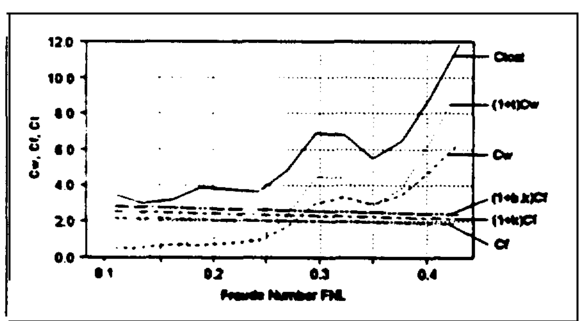

Figure A1.4.5
ITTC 1978 Approach

The factor b can be considered **to be independent** of the speed. A typical **illustration** of the variations of the b **factor** with **S/L** ratio is shown in figure A1.4.6, taken from reference 6. S is the distance between the **centrelines** of the two **demi-hulls,** figure A1.4.1, and L is the length on the static waterline.

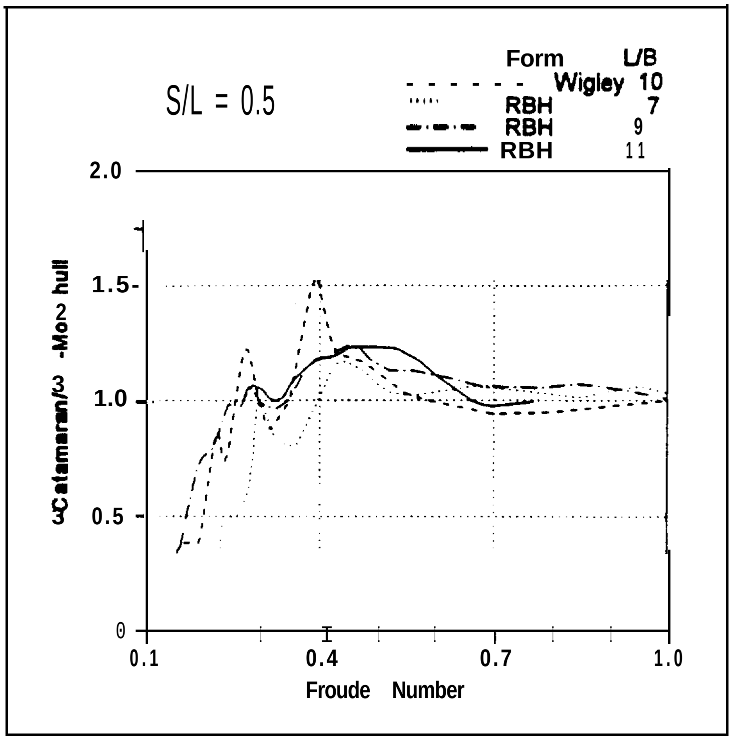

Figure A1.4.10
Wave Resistance Factor, S/L = 0.5

Following the ITTC 1957 approach the resistance coefficient of a catamaran can be expressed as

$$C_{tcat} = C_f + (1+f).C_r$$

where

$(1+f)$	=	Residual resistance interference factor.
C_r	=	Coefficient of residual resistance for the single demi-hull in isolation.

This **is** illustrated in figure A. 1.4.11.

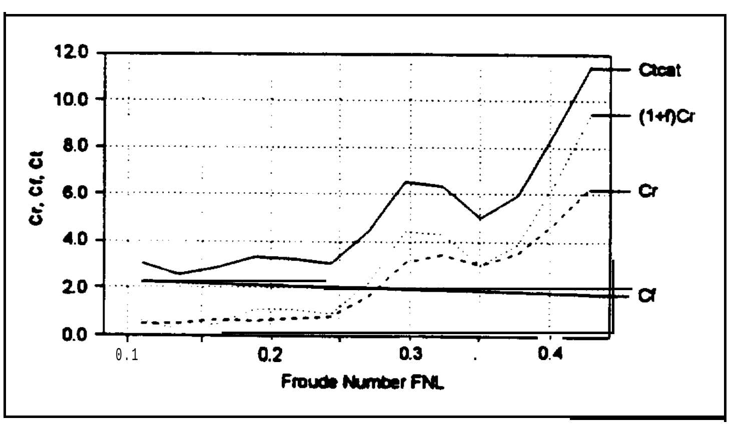

Figure A1.4.11
ITTC 1957 Approach

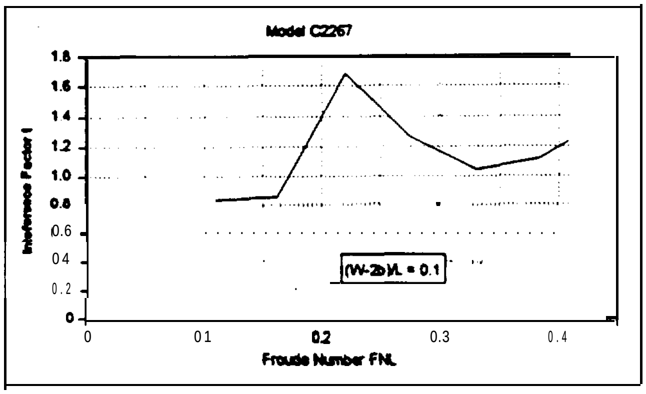

Figure A1.4.12
Interference Factor for
Asymmetric Hull Catamaran

The interference **factor** f is dependent on Froude number, and the same considerations apply as for the t factors. Examples of the trend of the (1 + **f**) factor with Froude number for different gap ratios are shown in figure Al **.4.12** for a catamaran with asymmetric demi-hulls and in figures A1.4.13, A1.4.14, A1.4.15, Al **.4.16 and** Al **.4.17** for catamarans with symmetric **ones.** The interference factors (1 + t) and (1 + **f**) are very dependent on the gap ratios as defined in section 1.4.3.1, the smaller the gap ratio, the more pronounced the hollows and humps of the interference factor vs. speed curve.

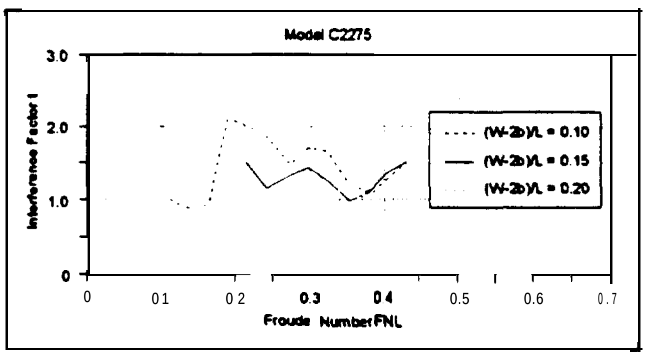

Figure A1.4.13
Interference Factor for
Symmetric Hull Catamaran

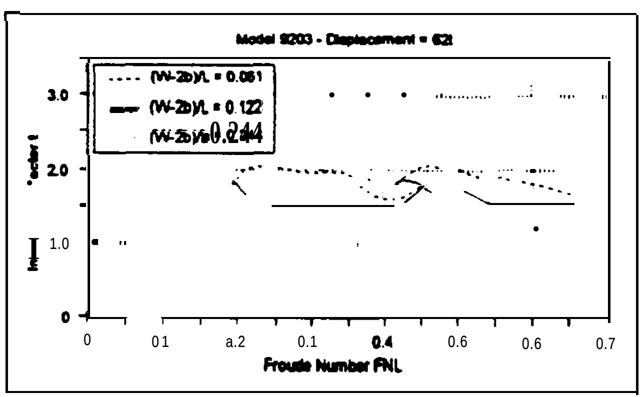

Figure A1.4.14
Interference Factor for

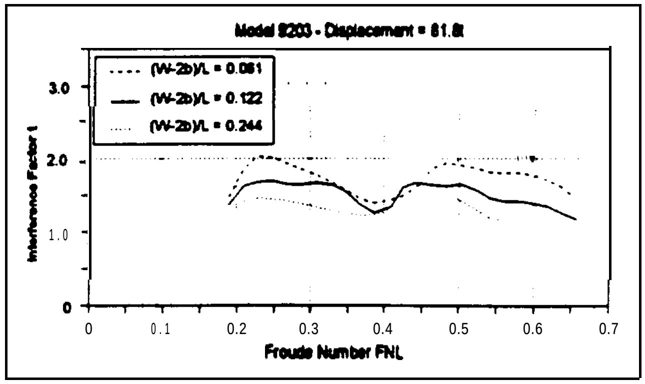

Figure A1.4.15
Interference Factor for
Symmetric Hull Catamaran

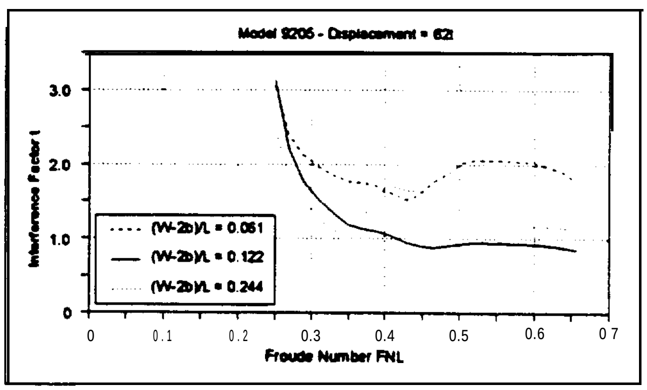

Figure A1.4.16
Interference Factor for
Symmetric Hull Catamaran

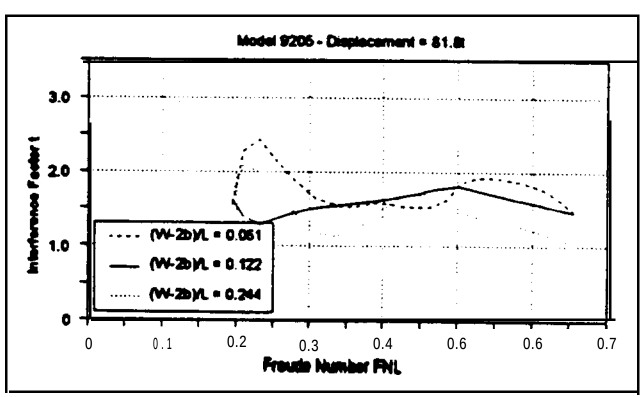

Figure A1.4.17
Interference Factor for
Symmetric Hull Catamaran

The forms of many slender catamarans are similar to those of the NPL series, so the methodology of reference 22 is applicable for preliminary resistance estimation. Results of towing tank teats of catamarans can he found in references 4, 6, 15, 16 and 24. Numerical methods to predict the resistance of catamarans are available commercially, reference 41 describes a computer code based on thin ship theory, or are under development, reference 42 describes a boundary element method applicable to high speed catamaran hull forms. Comparison of theoretical results with experimental measurements generally shows significant differences in absolute values, so such codes are only useful during preliminary design phases for optimisation and parametric analyses.

A1.4.5.2 Over Wave Resistance and Speed Loss

Added resistance in waves of catamarans is usually significant due to their high heave and pitch motions. Recent towing tank tests carried out in Italy for a displacement catamaran with asymmetric hulls resulted in the following figures when analysed using the ITTC 1957 correlation line

- **Jonswap H1/3 = 0.734m, mean period = 5 sec, heading 0 (head sea), FNL = 0.164**
  Increase of ship total resistance = 11%.

- **Jonswap H1/3 = 0.764m, mean period = 5 sec, heading 180 (following sea), FNL = 0.164**
  Increase of ship total resistance = 18 %.

- **Jonswap H1/3 = 0.552m, mean period** = 5 **sec,** heading 0 (**head** sea), FNL = **0.274**
  Increase of ship total resistance = 6%.

- **Jonswap H1/3 = 0.4806m, mean period** = 5 **sec,** heading 180 (following sea), **FNL = 0.274**
  Increase of ship total resistance = 7 %.

When evaluating speed loss in a seaway for fast vehicles with water-jet propulsion it should be borne in mind that additional problems such as cavitation or ventilation can occur.

A1.4.5.3 Propulsion

Depending on the speed and on other characteristics both water-jets and marine propellers can be selected. Other systems, such as magneto-hydrodynamic propulsion, are still in the early phases of study and are not yet feasible for operational craft. The catamaran configuration requires a two shaft propulsion configuration with one shaft for each demi-hull. It may be difficult to use more than two propellers or two water-jet inlets efficiently. The size of the propellers or water-jet inlets is usually closely related to the demi-hull beam.

Water-jet systems can be divided into two categories, depending on the inlet type used

- **Flush inlet**

- **Pod-strut inlet**

Either of these inlet types may be of fixed-area or variable-area, the latter **is useful for vehicles designed for operating at high speed and requiring high thrust levels at both low and high speed.**

Marine propellers can be of the fixed-pitch (FPP) or controllable-reverse pitch (CPP) type. CPPs have slightly lower design point efficiency than FPPs, but are often required in order to provide reverse thrust and for a better propeller-engine match. In cases where manoeuvrability and station keeping or dynamic positioning requirements are important azimuth thruster propellers can be selected as the main propulsor. This avoids the need for auxiliary azimuth or transverse thrusters. Propeller types can include subcavitating, supercavitating and superventilated, transcavitating and partially submerged or surface piercing propellers. Conventional subcavitating propellers are suited to low and medium speeds. At high speed they can suffer from blade cavitation erosion damage. Supercavitating and superventilated propellers are fully submerged and operate with gas cavities which spring from the blade leading edge, fully cover the back side of the blade, and collapse downstream of the blade trailing edge. They are suited to operation at all speed above 40 knots. The difference between supercavitating and superventilated propellers is only in cavity gas content, that is water vapour for the supercavitating and ventilated air for the superventilated. The superventilated condition is useful when it is necessary to reduce the propeller radiated noise. Transcavitating propellers have modified blade sections to achieve subcavitating operation at low speeds. Fully submerged propellers must have appropriate appendages to house the shafts, and these appendages impose drag penalties which become quite severe at very high speeds. A possible solution to this problem may be the partially submerged propellers which are usually transom mounted and therefore have a low appendage drag. They do however often suffer from vibration and strength problems arising from the cycling loading and unloading of the blades.

A good criterion by which to compare the performances of different propulsion systems is the overall propulsion coefficient opc, based on the net thrust (propulsor thrust less added drag due to the propulsor) rather than the more conventional propulsor open water efficiency. In order to estimate the opc it is important to know the value of various propulsive coefficients such as wake fraction (l-w), thrust deduction fraction (l-t) and relative rotative efficiency. Reference 40 presents a very useful chart which establishes reasonable bandwidths of achievable overall propulsive coefficients for flush inlet water-jets, surface piercing and submerged propellers, derived from experience of instrumented full-scale trials, figure A1.4.18. From the point of view of propulsive performance, the best choice is submerged propellers for speeds under 25 knots and water-jets for speeds over 40 knots, while for the intermediate range of speeds the water-jet system could still be a good choice.

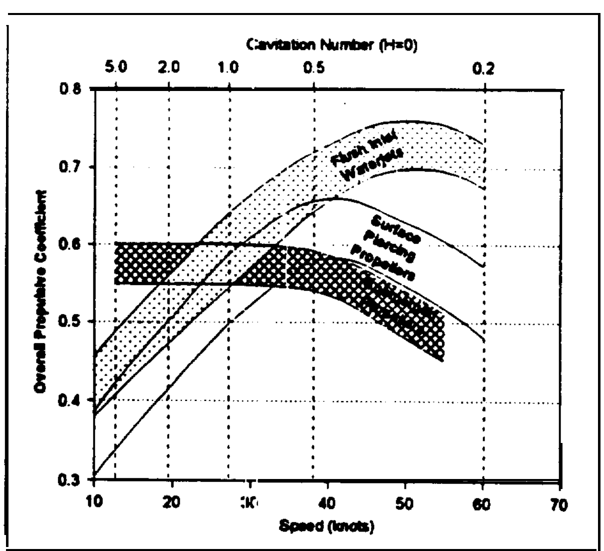

Figure A1.4.18
Achievable Overall Propulsive Coefficient
for Different Propulsors

In conclusion, for low and medium speed catamarans conventional s&cavitating propellers provide the optimum solution, while for high speed vessels a water-jet propulsion system with flush inlets could be a logical choice. in fact, **partially** submerged propeller **systems,** which at high speeds are more efficient than fully submerged ones, offer good performances and low system weight, but have **difficulty** in providing the large hump-speed thrust required by a catamaran. In addition they produce large transverse forces which generally cause problems in ship control and **manoeuvrability.** On the other hand, a water-jet propulsion system does offer some advantages such as

- **Steering**
  Reversing and good manoeuvrability over the whole speed range.

- **Protected installation** and shallow dmught

- **Low hydroacoustic** and internal noise and vibmtion
  Compared to propellers.

- **Good fuel economy**

A1.4.6 Sea-Keeping

A1.4.6.1 Sea-Keeping Qualities

The sea-keeping problems specific to a catamaran can be **summarised** as follows

- Hydrodynamic loads on the cross structure
  These are primarily bending moments and vertical shear.

- **Cross-structure slamming**
  Both its frequency and magnitude.

- Relationship between the natural pitch **and roll periods**
  This can result in the occurrence of undesirable corkscrew motions.

- Magnitude of **lateral accelerations**
  Particularly in the bridge area.

- **Roll motions**

As for **monohull** ships, the problems of deck wetness forward, bow slamming and bow acceleration must **be considered in the design of catamarans. The** main difference between a **monohull** and a catamaran with respect to the pitch motions is the fact that, due to the slenderness of the demi-hulls, catamarans suffer from a **lack** of resistance to pitching, **ie.** low pitch damping, especially at high speed in head seas.

In order to identify the design parameters relevant to sea-keeping behaviour it is convenient to separate the primary hull parameters, related to a single **demi-hull,** from those relating to the cross-structure parameters characteristic of a catamaran **configuration. In** the former group are the length-to-beam ratio **L/B and the beam-to-draft** ratio B/T. At high speed the longitudinal separation between the LCB **and LCF is also likely to play an** important role. In the latter group are the hull separation and the vertical distance between the **wet-deck** and the water surface.

Cross-structure slamming is a problem unique **to** the catamaran which may greatly affect the design. Since it is not always possible to provide sufficient **wet-deck clearance** to completely avoid slamming occurrence, it is necessary to evaluate the number and magnitude of the water contacts and identify those which are **likely** to **generate** a slam-like response. Slamming is a function of the elastic characteristics of the ship and a well established **criterion** is not presently available. **Recourse** must he made to general experience of bow damming and to experimental evidence, both model and full-scale, specific to catamarans. The frequency of water contacts and of slamming may be strongly influenced by most of the geometric parameters so far identified. The primary factor is certainly the wet-deck clearance while increasing B/T decreases slam occurrence as a consequence of the increased damping. The effect of L/B is the least significant. The magnitude of the slam pressures is not greatly affected unless there is a large variation in the relative motions.

The very large transverse metacentric height radically differentiates the roll of a catamaran from that of a monohull. In particular this leads to a general reduction of roll angle and lateral accelerations which, in conjunction with the natural pitch period, has a marked effect upon the habitability of the vessel. In this respect it is convenient to consider how human factors are affected by the wave-induced ship motions. The dominant effects for a catamaran are the accelerations, the roll angle and the random movements of the deck plane generally described as a corkscrew motion. Accelerations and corkscrewing motions are responsible for motion sickness of the crew whereas the roll motion impairs the motor capability of the personnel. This can be further compounded by the fatigue which results from continually attempting to adjust to the corkscrew motion. While the relationship between linear accelerations (either vertical or lateral) and motion sickness is quite well understood, knowledge of the effects of corkscrew motion upon seasickness is rather scarce but it is generally agreed that as the natural pitch and roll periods move progressively closer together the resulting uncertain angular motions are increasingly confusing to the human vestibular system.

The L/B, B/T ratios and wide hull separations of catamarans result in small differences between the natural periods. The effects of parameter variation on lateral acceleration does not seem to be very significant, wider hull separations show benefits in operability related to changes in lateral accelerations. In the case of roll motion, catamarans do not generally roll severely in bow seas when underway. Only in beam or quartering seas at slow or zero speed are roll angles large. The roll motion shows a greater sensitivity to dimensional variations than do lateral accelerations, but the trends are similar.

As for monohulls, the forebody motions are the dominant factors in determining the voluntary speed reduction of a catamaran in a seaway. These result in slamming, deck wetness and bow accelerations. For a catamaran, bow slamming is the predominant of the three effects. However it must be noted that cross-structure slamming is always the limiting factor. The effect of L/B is not very significant. Changes in B/T are of more interest as the extra damping of the hull with increasing beam reduces deck wetness and to a lesser extent the vertical accelerations. There is virtually no change in slamming because the beneficial effects of the extra damping are cancelled out by the reduced draft.

To summarise the effects of dimensional variations on sea-keeping design.

- **Length/Beam** ratio
  The effect of L/B is quite small so that the choice of L/B can be safely based only on powering and general arrangement; considerations.

- **Beam/Draft** ratio
  The B/T ratio of the hulls should be as large as practical in order to achieve better damping, lower bending moments and vertical shear on the cross-structure, and reduced roll angles in beam and quartering seas.

- **Hull separation**
  The hull separation will have to be quite small in order to keep sufficient separation between the natural roll and pitch periods, which may conflict with powering requirements.

- **Wet deck clearance**
  It is essential to maintain a wet-deck clearance which ensures the operability of the ship. In practice voluntary speed reductions will result from cross-structure slamming rather than bow slamming or bow acceleration. Only in the case of a low forecastle deck would deck wetness play an important role along with cross-structure slamming.

- **Displacement**
  Deviating from the design displacement always seems to be deleterious. It is true that increased displacement will generally decrease vertical shear force, bow slamming, roll angle and lateral accelerations, but it will also substantially increase the cross-structure bending moments, the deck wetness and the cross-structure slamming. During the design process careful control should therefore be paid to maintaining weight margins.

A1.4.6.2 State-of-the-Art of Catamaran Sea-Keeping Codes

Twin-hull motion problems have to date been studied by means of strip-theory incorporating exact 2D interaction solutions, references 27, 32, 33, 34 and 35. The strip-theory approach assumes that the wave energy only flows in the transverse direction, therefore it cannot account for the important 3D effects such as the dissipation of the wave energy between the hulls and the drastic change of 3D wave characteristics with increasing forward speed.

Recently an exact 3D Green function method was applied to the catamaran problem in order to account for the forward-speed effects, reference 30. However the computation time is enormous if a reliable numerical accuracy is desired due to the number of panel elements required.

Some innovative approaches specific to high-speed problems have recently been developed such as

- **Faltinsen's extended strip-theory in FASTSEA**
  This does not account for hydrodynamic interaction between the hulls.

- Chapman's pseudo 3D theory
  Reference 36.

- **Rankine panel method SWAN**
  Reference 3 1.

- **Hanaoka's** thin-ship theory
  Reference 38.

The paper in reference 28 extended unified slender-body theory to catamarans for the zero-speed case and the paper in reference 29 implemented this approach for the forward-speed case. However there is still no theory which can bridge the gap between zero and high speeds and can also be implemented computationally with relative east. The paper in reference 37 performs a comparison between the SWAN code and FASTSEA strip-theory for a catamaran in terms of the heave and pitch response in head seas at a Froude number of 0.45 for three different hull separations. The results for infinite and for 0.3L separation arc quite close for the heave response such that the differences can be explained in terms of interference effects. These effects appear huger for the pitch response. The paper in reference 26 illustrates the preliminary results of a correlation study between numerical and experimental results carried out on two displacement catamaran hull configurations, one with symmetric and the other with asymmetric demi-hulls. Three different computer codes were used,

- **2D strip-theory code**
  Based on conformal mapping technique and with no hydrodynamic interaction between the hulls.

- 2D strip-theory code
  Based on Frank close-fit technique and accounting for hydrodynamic interaction

- **3D diffraction theory code**
  Specifically adapted for catamaran configurations.

The second code was found to be the most reliable.

The computer code in reference 43, like others available on the market, is claimed to be applicable to both monohulls and catamarans. It is based on the strip theory and doesn't account for any interaction between the two hulls. For simple symmetric hull forms the accuracy of the heave and pitch responses are found to be adequate for early stage design optimisation. The paper in reference 39 evaluates the hydrodynamic coefficients and responses for heave and pitch for high speed monohulls and catamarans in regular waves using 2-dimensional strip theory and 3-dimensional panel source distribution methods. It compares the predictions with experimental model test data for various speeds and headings for different hull forms and hull separations. The codes were found adequate at low speeds and for narrow separations. When either the speed or separation was increased, both methods overpredicted the responses.

A1.4.6.3 Motion Damping Devices

Due to the importance of wet-deck slamming on cross structure design and vessel operability in rough seas, specific anti pitching devices for high speed catamarans have been developed. The hydrofoil catamaran (also called foilcat or hycat) is a hybrid design with hydrofoil wings spanning the space between the hulls. A virtual third hull placed above and between the two hulls in the bow zone, with a high deadrise angle bottom, normally completely out of water, is used in the wave piercing catamarans and in the tri-cat design to increase the damping at large pitch angles. Other active control surfaces used to reduce the motion amplitude of fast catamarans are active fins, of both conventional and inverted T form, and stem flaps. Different combinations are possible and are already used on existing catamarans. Passive devices, such as large bilge keels in the bow area, are useful in reducing the accelerations forward at low and medium speeds.

A1.4.6.4 Sea-Keeping Design Recommendations

The following recommendations can be made for improving the seakeeping of catamarans

- **Motion control**
  The installation of a motion damping device should be considered, in particular for fast catamarans.

- **Motion prediction**
  There still does not exist an easy and accurate prediction tool for catamaran sea-keeping, but strip-theory methods can be considered adequately reliable in preliminary and design optimisation stages.

- **Tank testing**
  The final design should be thoroughly tested in a towing tank to be sure that any unexpected hydrodynamic phenomena would not affect the expected performance of the vessel.

- **Crass structure slamming**
  A rational criterion for cross-structure slamming needs to be established.

A1.4.7 Structures

A1.4.7.1 Structural Design

The primary loads for catamaran vessels are the transverse bending moment and shear and the torsional (prying) moment. For fast catamarans the longitudinal bending moment due to impact on the water is also of some concern.

The maximum values of transverse bending moment and shear are likely to occur at zero speed beam seas. Indicative values for a preliminary estimation of the loads are reported in reference 8 and 20, the methodologies used in the calculations and the values obtained are more or less the same. Generally direct calculations will be required, using 3D finite element models of the whole ship with combinations of the following loads

- **Static loads**
  Weight and buoyancy in still water or in waves with different heading, oblique and transverse seas.

- **Dynamic loads**
  Impact pressures on the bottom of a demi-hull, and the inertial loads in the vertical and transverse directions.

A methodology for the direct calculation of catamaran structure, particularly for fast vessels, is given in reference 20. Reference 19 presents a theory for the computation of wave loads for twin-hull ships.

A1.4.7.2 Local Strength

The cross-deck structure is usually a point of concern from the point of view of local strength

- **Connection between the cross-deck and the demi-hulls**
  This is a common failure point under transverse and torsional loads.

- Bottom of **the cross-deck**
  The top of the wet tunnel can be affected by severe slamming.

- Moon pool **openings**
  If these are in the cross-deck structure they can create stress concentrations.

If the cross-deck length is less than the catamaran length then the cantilevered structure of the bow or stem has to be carefully checked under torsional load.

If motion damping devices like fins or bilge keels are fitted, then their structural design has to be carefully checked with the highest load occurring in the case of the appendage slamming.

A1.4.8 Heights

Catamarans are sensitive to changes in their draft, because if the height of the wet tunnel decreases below a certain limit negative effects can appear such as

- **Slamming of the cross-deck structure**

- **Increase in resistance**
  This is because of wave impact on the cross-deck due to the interference crests generated by the two hulls' wave patterns.

Light materials are the simplest way to limit the displacement and hence the draft. The need to limit the weight is particularly important for fast planing catamarans. Materials used for displacement catamarans are steel, light alloy or composites, either single skin or sandwich. For fast catamarans light alloy and sandwich composites are preferred.

A1.4.9 **Survivability**

Survivability is a combination of susceptibility and vulnerability.

A1.4.9.1 **Susceptibility**

The signatures of catamarans are usually of the same order of magnitude as those for monohulls with the following differences

- **Radar Crass Section (RCS)**
  The RCS from bow and stem sectors is increased by the reflector effect of the tunnel between the two hulls and under the cross-deck.

- **Underwater signatures**
  The underwater pressure generated by two slender hulls is usually less than that of the equivalent monohull. The same is also true for the wash. Siting equipment on the cross deck can also lower the magnetic signature by increasing its height from the water surface.

A1.4.9.2 **Vulnerability**

In a catamaran many important plants and systems are duplicated in the two hulls, and so the vulnerability to single failures or damage is reduced. The effect of the separation of the two demi-hulls at the waterline on the shock performance is claimed by some designers to be beneficial, however only extensive experiments could give a conclusive answer.

A1.4.10 **State of the Technology**

Hundreds of catamaran craft have been built so far and the majority are in commercial service in various countries world-wide. In the military field there have been very few applications.

The majority of fast catamaran designs come from Australia, particularly the wave piercing catamaran concept, followed by Norway and the UK. There have also been examples from other countries. The conventional displacement catamaran designs come from many different countries, lead by Australia, France and Norway.

The state of the technology in terms of design procedures is therefore well established, but for performance and sea-keeping characteristics prediction towing tank model tests arc still the more reliable choice. Computer codes are available, but their use is still limited to optimisation during the preliminary design stages.

A1.4.11 **Overall Advantages and Disadvantages**

The main advantages of catamarans compared to monohulls are

- Larger deck area per tonne of displacement
- Possibility of achieving higher speeds with a limited cast
- Reduced amplitude of roll motions

- **Higher initial stability**
  Consequent possibility of higher GZ.

- **Reducedwash**

- **Potential to easily install moon-pools**

- **Better manoeuvrability**
  Due to the larger separation of the two propellers.

- **Better survivability**
  Due to tbe duplication of many plants and systems in the two hulls, main engines, steering systems, etc.

The main disadvantages are

- **Larger frictional resistance**
  Due to the larger wetted surface. The consequence is a larger power required at low speed for the same displacement.

- **Possible increase in the wave resistance**
  Due to interference between the waves generated by the 2 demi-hulls.

- **Greater heave and pitch motions**

- **Lower periods of all motions**
  Consequently there are greater accelerations.

- **Possibility of coupling between roll and pitch**
  The so-called corkscrew motion.

- **Structural problems of the cross-deck structure**
  Due to the transverse bending moment and shear and torsional moment and the consequent need for direct structural calculations.

A1.4.12 Concluding Remarks

Catamarans are well proven in commercial applications, usually fast ferries. They offer some advantages over monhulls and have some drawbacks but they offer a low risk approach for applications needing large deck areas and possibly higher than normal speeds.

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Al.5 TRIMARANS

A1.5.1 Introduction

Trimarans are generally configured as having a long slim low resistance centre hull with two identical smaller hulls, one each side, desigued to provide stability. The three hulls are connected by a cross structure which in its simplest form consists of beams but is more likely to he a complete assembly integral with the main hull structure. The use of the trimaran form for powered craft is a comparatively recent development and so there is a lack of reliable design data available.

This section describes the current state of the art and provides guidance on powered trimaran design considerations based on the results of basic research and concept design studies.

Al.52 General Description

A1.5.2.1 Historical Review

The earliest form of trimaran craft was probably the outrigger canoe which originated in Indonesia (reference 1). Since then the majority of trimaran designs to have actually got to sea have been offshore racing yachts developed specifically to travel fast continuously over large distances. The transition from sailing Trimarans to powered Trimarans was pioneered by Nigel Irens who in 1986 developed Ilan Voyager a 21 metre 3.4 tonne vessel.

The outriggers on Ilan Voyager were designed to just touch the water surface when the craft was stationary and the "zero buoyancy" of the outriggers enabled the vessel to require an installed power of only 186 kW, and yet still be capable of 28 knots. In 1990 Ilan Voyager proved her viability as a seaworthy and fuel efficient craft by circumnavigating Britain at an average speed of 20.7 knots completing the 1568 nautical mile journey without refuelling. For this achievement she won the trophy for the fastest powerboat circumnavigation of Britain.

The idea of stabiising a very slender monohull with outriggers of low displacement was proposed within the UK Ministry of Defence as part of a project to reduce surface ship propeller noise. It was proposed to mount tractor propellers on the fore ends of the side hulls of a slender trimaran enabling them to operate in virtually open water. This however was not pursued further.

Design studies were conducted at University College London into the use of large powered Trimarans to satisfy a variety of ship roles. Designs for Frigates, Offshore Patrol Vessels, Aircraft Carriers, Destroyers and Ferries were worked up. Areas in which the Trimaran concept showed advantages included ship layout, survivability and powering. No serious unacceptable penalties were identified. The various designs which were produced are described in (references 2 and 3).

Studies have also been performed in Japan aimed at reducing the resistance of high speed displacement ships. The development of narrower monobulls led to the need for small side hulls in order to provide sufficient stability. A theoretical investigation of the wave resistance of such a configuration was performed by Suzuki and Ikehata (reference 4).

A detailed design study for an Anti Submarine Warfare frigate has been performed by Summers (reference 5). This study is significant as trimaran, SWATH and monohull designs were produced to meet the same requirement. Sufficient work was performed to demonstrate the potential advantages of the Trimaran form in the areas of

- **Powering**
- **Layout**
- **Seakeeping**

- **Survivability**
- **Stealth**
- **Cost**

A potential fast Commercial Ferry application is described in reference 6.

A1.5.2.2 Vehicle Description

Trimaran ships have a slender main hull with two smaller side hulls. The centre main hull will typically have a length to breadth ratio of between 11 and 19 while the side hulls will have a ratio of from 15 to over 30. The hulls will be connected by a box like cross deck structure integral with the main hull and with the side hulls mounted beneath it. A length to overall beam ratio of between 4.5 and 7 can be expected. The smaller hulls contribute approximately 8% of the total displacement of tbe vessel with an overall length up to about half that of the main hull. The general Trimaran configuration is shown in figure A1.5.1.

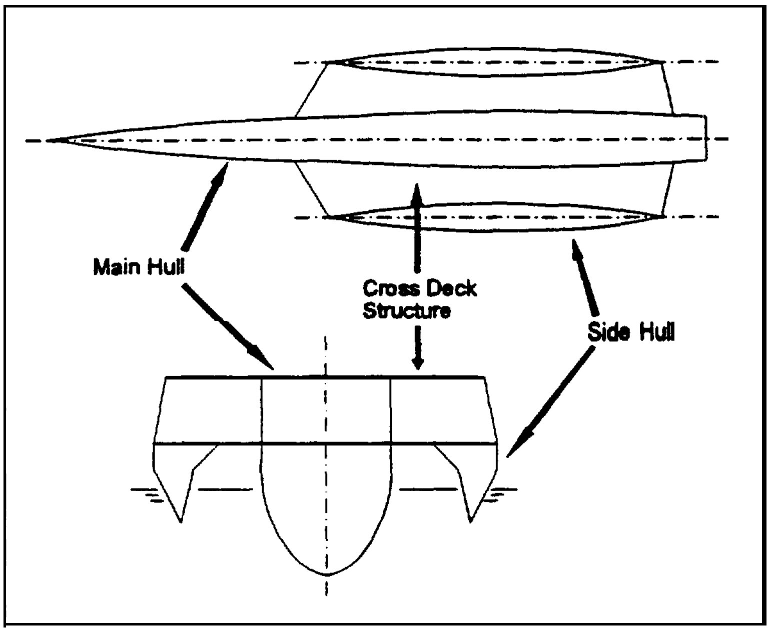

Figure Al.51
Trimaran Configuration

The slender main bull offers low wavemaking resistance and the side hulls need to be positioned to reduce wave interaction effects although other considerations may prevent an optimum minimum resistance being obtained in practice.

The vessels can conveniently be powered by either propellers or water jets although the slender main hulls do impose constraints on propulsion machinery layouts. It is possible to install machinery and propulsors in the side bulls although this will tend to increase tbeii size and bence resistance. The advantages of distributed propulsors on survivability and manoeuvring may be considered to outweigh the resistance penalties for some applications.

The outstanding features of the Trimaran are summarised below:

- **Lower resistance**
  The ability to operate at higher speeds for the same installed power as an equivalent monohull or conversely the ability to attain the required speed with a lower installed power. This is true for higher speeds where the wavemaking component would dominate monohull resistance.

- Wide cross deck structure
  The wide cross-deck structure provides a useful large deck area allowing flexible deck layout arrangements. In addition the extra length can allow more freedom in positioning motion critical accommodation and equipment in more favourable positions. For example helicopter landing areas can be moved much further forward of the transom.

- **Good seakeeping**
  The form affords a good seakeeping response in pitch and roll motions. Tbe improvement in pitch motions is due to the greater length of the trimaran over an equivalent monohull design. Roll response is affected by the beam, GM and inertia. As with monohulls and catamarans too high a GM will produce an uncomfortable motion. Provided natural roll periods are selected carefully the trimaran should have no worse roll behaviour than a monohull.

- **Damaged stability**
  The side hulls provide good damaged stability. Studies have shown that damaged stability can he made to far exceed that expected for monohulls. Also damage control, fire fighting and even subsequent repair will be much simpler due to the accessibility provided by the platform cross deck structure. The net result is a higher damage tolerance for the trimaran than for an equivalent monohull.

Although Trimarans have been used extensively for non-powered vessels, care must be taken in selection of the trimaran hull form for powered craft. There are no hrge powered Trimarans under construction at present. The designer must be aware that ships below a certain size may make layout arrangements difficult as the cross-deck structure could become non-usable volume.

A1.5.3 Fundamental Features

A1.5.3.1 Hullform

A number of studies have been carried out to try and ascertain the criteria that need to be met to obtain an optimum design. In general the required benefits of the Trimarans are that of low wave mating resistance with improved stability and seakeeping. These are considered to be essential if they are to compete with monohull designs.

There are three elements to the Trimaran hull configuration and these are described in the next three sub sections.

A1.5.3.1.1 Main Hull

The centre main hull provides 90% or over of the total buoyancy. If a conventional monohull is taken as the starting point then the Trimaran centre hull is likely to be at least 20% longer and with 25% less beam. ‘his will result in an approximately 50% reduction in BM. The main hull is likely to have the following characteristics

- **Length/Beam** Ratio
  Typically in the range 11 to 19 in order to reduce the wave making resistance. The finer the hull the less resistance. As the hull length is increased so the Froude number will be reduced along with any trim and sinkage effects.

- Beam/Draft **Ratio**
  The hull should be as deep as possible with ratios ideally below 2.0. This will reduce the resistance and also the occurrence of bow emergence and slamming.

- Hull Depth
  A Trimaran hull will probably have greater depth than for an equivalent monohull in order to integrate the cross deck structure and layout into the hull and still provide adequate wave clearance.

- Block **Coefficient**
  The optimum block coefficient of the main hull will depend upon the design speed. For corvette type vessels operating at Froude numbers of approximately 0.5 the coefficient should be below 0.45. Faster craft, however, should have a block of about 0.35 while slower craft could have a higher value.

- **Sections**
  The hull form should have deep V sections forward transforming to fuller sections aft. The large draught will delay slamming onset and the V form will reduce the effects of slamming should it occur.

- **Transom Immersion**
  Transom immersion should be minimised and will depend on the propulsion configuration chosen. Waterjets will dictate a larger immersion than would be desirable from pure drag considerations.

A1.5.3.1.2 Side Hulls

The side hulls should be designed with the following characteristics in mind

- **Displacement**
  The side hulls purpose is to provide stability with minimum resistance. Their displacement should each be about 3% to 5% of the total. The figure will obviously vary with the vessel loading condition .

- Length
  The length of the side hull will be determined by damage stability requirements. A minimum length of twice the assumed damage length should be considered.

- Length/Beam Ratio
  The side **hulls** should be as long and thin as possible to minimise the wave making drag with an L/B ratio greater than 12 **and perhaps as high as 30** or more.

- Draft
  The draft of the side hulls will be determined by the requirement to provide adequate stability at all loading conditions. It is beneficial to keep the draft as low as possible in order to minimise the resistance.

- Hull Shape
  It is possible that asymmetric hulls could be used with flat inner surfaces in order to reduce the interference effects with the main hull. There is however the danger that asymmetric hulls could create course keeping problems in a seaway. For Trimarans the length to beam ratio is so large that it is questionable whether this would be significant.

- **Sections**
  In order to reduce wetted surface area a circular section could be considered. Further forward a V form will reduce slamming and wave impact loads. The sections should be flared above the waterline in order to provide adequate but not excessive intact stability. A fillet should be provided on the inner side where the hull joins the cross structure. This is needed in order to avoid sudden changes in the waterplane as the craft heels and so smooth the GZ curve.

- **Transom**
  If there is no propulsion machinery in the side hulls then it may be beneficial to eliminate the transom from the side hulls in order to reduce drag.

- **Main/Side Hull** Separation
  To reduce the resistance interaction effects a fairly large separation is required between the main hull and side hulls. However the side hulls must not capture the bow wave from the main hull as this causes an increase in resistance. Stability requirements will determine the minimum separation.

- **Side Hull Fore and Aft Position**
  The fore and aft position of the hulls could have a very significant effect on the resistance of the craft particularly at higher speeds. It is generally advantageous to place the side hu!! further aft in order to avoid interfering with the bow wave of the main hull. Layout considerations may we!! require the cross deck and side hulls to be moved further forward.

A1.5.3.1.3 **Cross** Deck **Structure**

- **Surface Clearance**
  To prevent wave impact on the underside of the cross-deck structure a large air gap is preferred. At least half the freeboard at the stem of the main hull should be a value to be aimed at.

- **Volume**
  The cross deck structure provides a significant proportion of the usable internal volume of the vessel. It is also important in terms of the vessel's stability as it heels and so subdivision is an important consideration.

- **Height**
  The cross deck structure really needs to be at least one deck high in order to provide useable space inside. This then requires the main hull depth to be sufficient to allow adequate load transmission and so the centre hull may be deeper than for an equivalent monohull.

A. 1.5.3.2 **Stability Requirements**

'his has proven to be the most difficult aspect of design. Studies have shown that the Trimaran will follow the trend of monohulls, in that larger vessels will meet stability criteria easily whilst smaller vessels can suffer problems.

Main hull subdivision is governed by flooding criteria only and has no effect on stability.

The outer sections of the cross deck structure need to be subdivided as these will become submerged as the craft heels. It may be that this subdivision does not need to extend the full width of the vessel so facilitating a flexible layout. The cross deck structure provides a very large reserve of buoyancy with a large range of intact stability. ultimate stability should not be a problem with these vessels

Research has shown that on smaller Trimarans, intact and damaged stability criteria may be met easily even if the side hulls are flooded. (On the basis that a full compartment can take on no more water). In fact the loss of tank contents on the damaged sides may allow the vessel to heel away from the damage.

The permeability of the side hulls has a major effect on the damaged stability of a Trimaran. As a result any method by which the permeability of the side hulls can be reduced will show to advantage. For smaller Trimarans this can be achieved by foam filling the side hulls rather than leaving them void. On larger Trimarans three options are possible. Again, they can be filled, they can be used to house machinery powering propulsors in the side hulls or they can be utilised for tanks.

The latter solution is most effective if the side hulls are divided into ballast and or fuel tanks. Thus, once fuel is used up ballast can be taken on allowing the vessel to operate at a constant displacement. An alternative but more expensive solution to having separate tanks is to have a salt water compensating fuel system but this would only really be suitable on a large, say 2500 tonne plus, Trimaran due to the added complexity.

Ballast tanks could also be used to heel the vessel away from the damaged side by flooding them.

When considering subdivisions of the side hulls and cross-deck, to ensure adequate damaged stability a suitable compromise must be maintained between too few and too many bulkheads. The designer needs to ensure that floodable length criteria are met whilst also ensuring that the layout flexibility is not unduly restricted by the addition of excessive watertight bulkheads.

A difficulty that has to be overcome is that the vessel may attain a high heel angle before the cross deck becomes submerged and contributes to the stability. This can be eased by lengthening the side hulls (a minimum of twice the assumed damage length) or providing a means to flood part of the main hull, thus reducing the heel angle.

A1.5.3.3 Operating Speed Range

The operating speed range has not been fully explored. However, the inherent low wavemaking resistance associated with the hull form lends itself to designs with higher top speeds or high endurance cruising speeds. At lower speeds careful design is needed to ensure that skin friction and transom drags do not increase the trimaran resistance over that of an equivalent monohull. Careful positioning of the side hulls is needed to ensure optimum resistance characteristics. For a particular model test of a 95 m vessel the side hull and interaction resistance accounted for some 23% of total resistance at a speed of 30 knots. Side hulls positioned towards the rear of the main hull seem to be favoured. The Trimaran hull is particularly suited to higher speeds at which monohulls tend to trim aft.

A1.5.3.4 Manoeuvrability

It is likely that the relatively long hull will make the Trimaran very directionally stable. The results of some model tests indicate that turning performance for a vessel with all propulsors in the centre hull may be slightly worse than for an equivalent monohull. However if the Trimaran has prqpulsors in the side hulls it is likely to have much improved mamuvrability. Conversely the negative side to this is the consequence of failure or damage to one of the side hull propulsion units. The ship is likely to be very difficult, if not impossible, to control with such an asymmetric propulsion configuration.

Low speed manoeuvring can be provided by bow thrusters. The turning moment available will be considerable due to the length of the hull.

A1.5.4 Layout Arrangements

A1.5.4.1 Accommodation

For Trimaran craft of appropriate size the height of the cross-deck structure, at a full deck height, provides a very flexible area for accommodation layout.

Positioning of the accommodation and operational spaces in the cross deck structure located in the middle third of the vessel, near to the pitching centre, will increase crew functionality in higher sea states.

A1.5.4.2 Deck Space

The large area of deck afforded by the cross-deck structure, lends itself particularly well to helicopter operations. The position of the landing area in a region of reduced motions, means that operations may continue at high sea states. Similarly ship's boats can be located in an area where they can be handled more easily.

The more square area available for layout offers the following advantages over the long narrow area available on a monohull

- **Access**
  There is greater flexibility in positioning passageways.

- **Functional Grouping**
  Similar function compartments can be collocated more easily, improving efficiency and perhaps reducing build costs through opportunities for use of modules.

- Protection
  Critical operational spaces can be positioned towards the centre of the vessel and be shielded by less important spaces.

The upper deck area forward of the cross deck will usually be sufficient to house a weapon system in the conventional position. The fineness of form at the bow may lead to the foredeck beiing extremely wet. This beii so the designer should utilise the deck space carefully and avoid the requirement for manned deck operations in this region. There may also be limitations on the usable space within the forward part of the hull due to its lack of beam.

Topsides arrangement is generally easier and more efficient than for an equivalent monohull, as the overall length is greater than the minimum normally considered to be required for a typical weapon payload. Weapons and sensors may be better distributed thus improving arcs of fire and reducing interference. It is also envisaged that all the features required for achieving a low Radar **cross section** of the top sides can be incorporated on Trimarans.

The side hulls are of limited use for layout because of the need for subdivision in order to meet damaged stability requirements. If propulsion or stabiliser units are to be fitted then their beam may have to be increased. They do provide useful volume for tanks.

A1.5.4.3 Machinery

The reduction in power requirement leads to the size of engines being reduced. The centre hull will generally be devoted to the main machinery installation and the beam limitations do impose some constraints.

The layout of the main hull will be dominated by the needs of the machinery package. If the engines are below the cross deck then adequate height must be provided. If accommodation is to be sited above then appropriate silencing arrangements will be needed.

The shafting and propulsion arrangements depend largely on the design speed of the vessel. It is likely that for a low speed vessel there will be adequate shaft and propulsion clearances for a twin screw or jet arrangement. For a hi* speed vessel it is possible that a large central main engine and propulsion system may be the most efficient. Propeller discs may extend outside the beam but they are of course protected to an extent by the side hulls.

The positioning of machinery in the side hulls allows greater potential for redundancy but the space is severely constrained and so this is only really viable on larger vessels.

Reduced power requirements for similar speeds will lead to the physical size and quantities of machinery beiig smaller. This has useful implications for simplifying removal routes, accompanied by ease of accessibility and maintenance. Provided they can be fitted on absorbent mounts the noise signature of smaller engines may be lower.

A1.5.4.4 Habitability

A high level of habitability should be achievable. The primary reason for this is that the Trimaran layout offers the potential to site all accommodation and operational spaces in the middle third of the vessel's length. This not only gives the advantage of reduced motions and thus reduced fitigue but also the ability to locate all related compartments in convenient functional groups.

The reduced power requirements of a Trimaran lead to smaller machinery packages than a comparable monohull potentially reducing internal noise and increasing crew comfort. It may also be possible to provide greater separation of accommodation from machinery compartments.

A1.5.5 Resistance and Powering

A1.5.5.1 Resistance Components

There are several elements making up the total resistance to be considered

- **Main Hull**
  When considering the main hull in isolation, predictions can be made using standard series such as Taylor-Gertler or Series 64, the former beii more suitable for lower Froude numbers and the latter for higher. The Trimaran's slender form and its longer length lead to a reduction in the wave-making component dominant at higher Froude numbers as compared to conventional monohulls.

- **Side Hull**
  Side hull resistance can again be predicted by standard series.

- Interaction Effect

  Interaction between side and main hulls contributes up to 10% additional resistance. There are two components to this. The first is a potential increase in viscous resistance due to pressure changes, probably very small. The second is wave interaction between the three hulls. Typical teat results showing this interference are shown in figure A1.5.2. Moving the side hulls fore and aft will affect this.

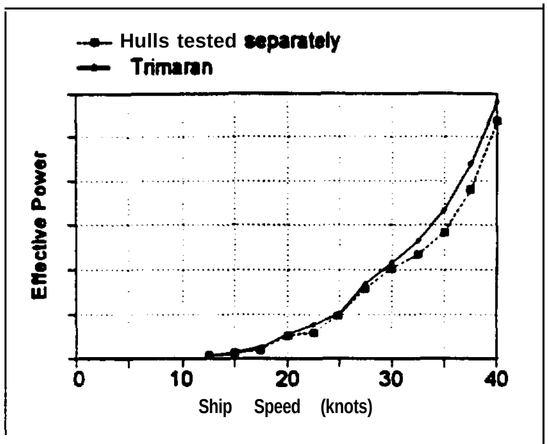

Figure A1.5.2
Interference Effects on Power

- Other Components

  The windage component will depend upon the frontal area and with a full width cross deck and superstructure this could be considerable. The effects of appendages should be calculated and allowed for in the same way as for other craft.

The net effect of all resistance components when comparing a Trimaran against an equivalent monohull is an increase in skin friction drag, through greater surface area and viscous interaction effects, and lower wave making resistance. This means that the Trimaran is likely to have the same or slightly better cruise speed resistance but could show more advantage as the speed increases.

A1.5.5.2 Over Wave Resistance & Speed Loss

No tests have been carried out as yet but it is felt that the fineness of form will lead to the vessel cutting through waves and thus maintaining higher continuous speeds in higher sea states than an equivalent monohull.

Cross-deck slamming of the nature that occurs on Catamaran and Swath type vessels, is likely to occur on Trimarans but the effects should be much less severe due to the cross-deck structure being situated well aft.

A1.5.5.3 Propulsion

Trimarans may be powered by propellers or waterjets, however at Froude numbers less than 0.5 waterjets show a reduction in efficiency. Both propellers and waterjets give good efficiencies at high speeds. The selection of propulsion system must be done at an early stage as the hull form required for waterjets is very different to that needed for a conventional propeller. The use of waterjets on too low a speed craft will result in a hullform with poor resistance characteristics. The hull will have excessive transom immersion and an LCB position too far aft.

A1.5.6 Seakeeping

A1.5.6.1 Motions In A Seaway

The vertical motions of heave and pitch could be predicted by using strip theory computer analysis of the main hull only. The effect of the side hulls could be considered by adding in their waterplane and section areas to the main hull at the appropriate longitudinal positions. It is thought, however, that the small waterplane area, volume and the slenderness of the side hulls will contribute little to the pitching and heave response of the vessel. Model testing has shown that pitch resonance seems to occur at wavelengths shorter than the ship length and that the resonant peak is reduced compared to that which would be expected for a monohull. Overall the evidence is that Trimaran vertical motions are very similar to those of a monohull of the same length. Due to the longer length of the Trimaran compared to a monohull designed to the same requirement the overall pitch response of the Trimaran will thus be better. The Trimaran also has an advantage in that the internal layout constraints will tend to place areas affected by motions farther away from the ends of the ship than would be possible on a monohull.

Roll motion response is very affected by the vessel's natural roll period, itself a function of waterplane, mass inertia and GM. Resonant motions can occur in quartering seas and must be avoided by selection of a suitable natural roll period. Generally a high roll period gives bad stem sea and good bow sea responses while a low roll period gives good stem sea and bad bow sea responses. Overall it would seem that designing for a roll period that would be appropriate to an equivalent monohull will provide very similar responses. This would require a comparatively high GM as the Trimaran inertia is larger. The inertia itself is extremely sensitive to the beam and can be changed by a very small movement of the side hulls.

In order to ease the roll motion care should be taken to ensure that the GZ curve contains no discontinuities. This can be achieved by flaring the side hulls and providing a fillet at the side hull to cross deck connection.

It should be noted that trimarans could require roll stabilisation just as with a monohull. This could be provided by fins or tanks as appropriate to the size and layout of the vessel.

A1.5.6.2 Slamming and Wetness

The slender hull and V shaped sections lessens the impact of slamming. With the very fine bows of a Trimaran deck wetness may be a problem for manned operations on the foredeck. Visibility from the bridge could also be affected by wind blown spray. This could be prevented by increasing the freeboard through the addition of another deck.

Cross deck slamming could also be a consideration and adequate clearance must be provided. A criterion has been proposed (reference 5) that the deck clearance should be half the sea state 6 wave height plus the bow down pitch.

A1.5.7 Structures

A1.5.7.1 Structural Design

The designer should be aware that there is very little data available from which to produce guidance on Trimaran loadings and so careful consideration should be given to each design.

- **Longitudinal** Bending

  The normal monohull criteria of longitudinal bending should be equally applicable to **Trimarans.** There is unlikely to be any difficulty in providing adequate longitudinal strength due to the depth of the main hull. The cross deck structure can also contribute to the longitudinal strength. Studies have shown that once the side hulls' length approaches 50% of the main hull length then the cross deck structure becomes very effective. It is likely that the flexibility in layout offered by the cross deck will mean that any superstructure can be broken up and made small enough to be non effective so reducing stresses in the deck houses.

- Transverse Bending

  Transverse strength should also be considered for the cross deck structure. There is very little data available on the loads to be considered. Although transverse bending can be the critical loading case for twin hulled vessels, the small size and displacement of the side hulls means that sea loads are unlikely to be so significant for Trimarans. The loading due to the cross deck and side hull being cantilevered off the main hull has been proposed as a design case, (reference 5). Two cases can be considered

  - **Side hull weight** alone

    Side hull **immersed to** bottom of **cross deck structure**

  These are shown in figure A1.5.3.

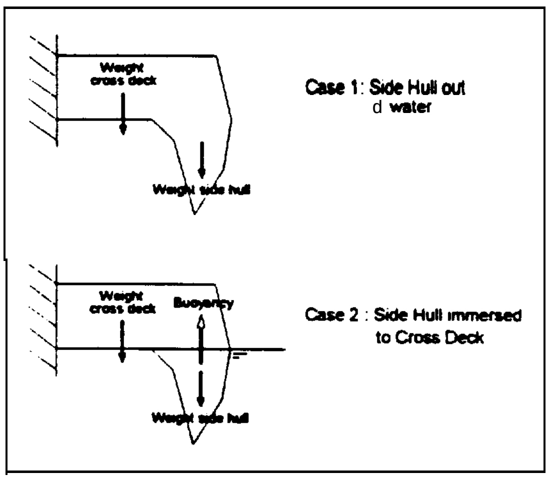

Figure **Al.53**
Transverse Loading Cases

- **Other Loading Cases**

  Other loading cases such as torsion in following seaways are perhaps unlikely to be as significant as for catamaran vessels as the side hulls provide so little buoyancy. However extreme damage cases could lead to asymmetric loadings on the cross deck structure. The long narrow forward part of the main hull will **need to be considered carefully.**

A1.5.7.2 __Local Strength__

Possible areas to be examined in detail are

- **Cross Deck**

  The discontinuity of the main hull at the ends of the cross deck will need careful reinforcement. The effect of wave impact on flat panels may be significant.

- **Side Hulls**
  The attachment of side hulls to the cross deck should be examined particularly if dissimilar materials have been selected. This is possible on smaller vessels where producibility considerations may lead to the use of unconventional side hull structures.

A1.5.8 Weights

Many of the normal weight groups can be estimated by scaling from monohull data. The biggest differences will be in terms of structure and machinery.

The structure can be estimated in three parts, the centre hull can be scaled simply from normal monohull experience while the side hulls and cross structure weights will have to be built up from lower level weight estimates. The net result will be a higher structural weight fraction for the Trimaran than for the monohull.

The machinery weights are likely to be lighter than for an equivalent monohull because of the lower power. Similarly the disposable load will be lighter with less fuel needed.

The overall weight of a trimaran will be close to that of a monohull designed to the same operational requirements.

A1.5.9 Survivability

Susceptibility coupled with vulnerability provides a measure of the survivability of the vessel.

A1.5.9.1 Susceptibility

This will depend on the vessel's signatures. Optimising the stealth characteristics of a Trimaran design is facilitated by the following features

- Noise
  The reduction in powering requirements could lead to a lower noise signature, provided machinery is mounted on absorbent mounts and propulsors are adequately designed.

- Infra Red
  The main machinery compartments (main hull) could be shielded by the side hulls. It is also possible to vent exhaust gases between the hulls, negating the need for an easily detectable funnel, and allowing the heated exhaust gases to be diffused before they become visible. However the designer must ensure that the exhaust gases are not blown back across the deck in unfavourable wind conditions.

- Radar
  The latest radar cross section signature reducing techniques can be readily applied to Trimarans. The large volume in the cross deck structure reduces the requirement for high superstructures and the large cross deck area provides good scope for shielding the topsides equipment of the vessel. Since the Trimaran can be made less sensitive to high top weight the use of radar absorbent materials for topside equipment is eased.

- Wake
  The likelihood of detection of the wake of the vessel will be reduced due to the reduction in wake generating wave making resistance.

- Magnetic
  The magnetic signature can probably be made comparable to monohulls but degaussing will be more difficult due to the complex shape.

A1.5.9.2 Vulnerability

The preceding features all reduce the chances of the Trimaran being hit, however in the event of a strike the following features can be incorporated.

Due to the stabilising effect of the side hulls the stability in the damaged case for a Trimaran will be greater than a monohull. The side hulls of larger vessels could possibly be filled with fuel oil or ballast water. After damage to the tanks the contents will run out and the vessel will roll towards the intact side and thus heel away from the damage. Smaller Trimarans may have to rely on ballasting the intact hull to achieve satisfactory stability. Damage to the main hull should not cause a risk to the ship's stability.

The fact that any centre hull machinery space could be shielded by the side hull reduces the likelihood of damage and so it is probable that the Trimaran will retain propulsion in the damaged state. If machinery is positioned in the side hulls then the designer should ensure adequate redundancy,, so that in the event of a side hull beiig damaged the vessel will still have propulsion capability. It should be noted that if propulsion is only available in one side hull the vessel will probably be directionally uncontrollable.

The wide cross deck structure should make fire fighting easier as any fire and smoke has to spread horizontally rather than vertically. Access and control should thus be easier.

A1.5.10 State of the Technology

Trimarans are a recent concept with no ships in service, there is therefore a lack of reliable design and test data available. However sufficient studies have been performed to show that the concept is viable and indeed may prove superior to other configurations for some purposes.

A1.5.11 Overall Advantages and Disadvantages

A1.5.11.1 Advantages

The Trimaran hull form exhibits some clear advantages over equivalent monohull designs.

- High Speed Resistance
  The high length beam/ratio of Trimarans can afford a lower resistance to motion. The increased skin friction resistance is offset by the much reduced wave making components. at lower speeds where skin friction dominates, the high wetted surface of the trimaran may require higher cruise powers than for the equivalent monohull unless care is taken in hull design. It should be possible to at least equal the monohull performance. Low maximum power requirements reduces both acquisition and running costs.
- **Stability**
  The configuration offers better damage stability.
- **Seakeeping**
  The extra length should produce a reduction in vertical motions in manned areas.
- Layout
  Topsides arrangements are less constrained than on a shorter narrower monohull allowing more efficient payload positioning. The cross deck structure offers convenient layout arrangements allowing concentration of living and working spaces to be positioned in the middle third of the vessel, where ship motions are reduced.
- Survivability
  The reduced constraints on topsides arrangement allows scope for straightforward application of signature control measures. The good damage stability characteristics together with the potential for damage tolerance through careful layout makes the trimaran potentially more survivable than other vessels.

- **Costs**
  Preliminary indications are that build costs for a trimaran may be similar to an equivalent monohull. This is because the reduced machinery sizes compensate for the cost of increased structure. The lower power results in a reduction in running costs.

- Upgrades
  There is potential for upgrade of the vessel as it's stability can be altered easily by alteration of the side hull position.

A1.5.11.2 **Disadvantages**

Any **new** concept does not come without its disadvantages. Those that have been identified are as follows

- **Classification and Standards**
  There are as yet no rules for the classification of **Trimaran** vessels in terms of either stability criteria, structural strength requirements or safety at **sea** considerations such as **IMO** regulations.

- **Docking**
  The longer length and greater beam will require larger berths and docks, There may also be particular difficulties associated with launching and docking, consequently procedures will need to be studied and perfected.

- **Manoeuvrability**
  The long fine hulls may lead to slow speed manoeuvrability problems. This can be alleviated by bow thruster arrangements.

- Machinery
  The thinner hulls impose constraints on machinery layout.

- **system runs**
  The extra length may increase the length and costs of some system runs needed. **This** can probably be alleviated by careful layout made easier by the fewer space constraints.

- **Degaussing**
  The degaussing of Trimarans will be made more difficult due to the complex shape.

- **Shock**
  The behaviour of **Trimarans** structures under shock is not known.

- **Risk**
  As the concept has not been extensively researched there is inevitably a level of risk attached.

A1.5.12 Concluding Remarks

It is **necessary to** point out that the **generalised statements for** guidance have been **formulated** on the basis of basic research and concept design studies only. It is always difficult to prove **such** research without **building** a prototype and testing it thoroughly.

There is little doubt that the **trimaran** concept is worthy of further development and promises distinct advantages for some roles. Unlike many other unconventional **hullforms** it can easily be applied to large craft, the upper limit of which has not yet been identified.

Although the concept is not yet in service the technical risks in implementing a successful design are perceived to be **low**

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Al.6 HYDROFOIL

A1.6.1 Introduction

This section presents information and design guidance on the main characteristics of the range of commercially built Hydrofoil Craft currently available and their possible use in military applications.

It should be noted that the term hydrofoil should more precisely be Hydrofoil Craft as the word hydrofoil should be used only to describe the lifting structure and the foil(s). As the foils fitted on the craft will operate in water they have been named hydrofoils to distinguish them from their air borne equivalents, aerofoils or wings. Technically hydrofoils are the surfaces or profiled bodies that produce the forces necessary to lift the craft attached to them out of the water. An aerofoil or wing moving in air produces lift for aeroplanes in the same manner. In spite of the very different type of fluid in which the two foils are immersed (air or water) the same principles will apply apart from the fact that water is some 800 times denser than air. In either case the lifting forces depend on the dimensions and the: particular shape of the body and on the relative speed at which it moves through the fluid.

A1.6.1.1 Historical Notes

Hydrofoil craft are not a new means of transportation as they have been around for some time. Early experiments can be traced back to the Rev. Ramus during 1870. Separate studies by Forlanini, in Italy and Hewitt during 1905 led to the construction of a ladder type fully submerged hydrofoil system. Building rights were bought by Graham Bell who together with Casey Baldwin produced, during 1919, a working prototype flying at over 60 knots, This craft led to the construction of a number of derivatives, some of them built by the British Admiralty during 1923.

As an alternative to the fully submerged ladder foil system a V shaped surface piercing hydrofoil was developed by the German Baron Hans Von Shertel who tested a number of craft in 1930. World War II gave a boost to the development of such vessels and a number of them were built for use as escort vessels for the German convoys cruising between Sicily and the northern region of Africa. After the war development was continued in Switzerland by Supramar, a company formed by Von Schertel and others. Carlo Rodriquez, a Sicilian baron, bought the building licence and from 1956 onwards became the world leader in hydrofoil craft construction. More than 200 units have been built so far, the very first under Supramar licence while all the others were the products of Rodriquez's own design team.

Surface piercing hydrofoils were also developed in other countries such as Canada which built a very innovative vessel, the Bras d'Or. This craft, of some 200 tons displacement, was capable of a speed of 62 knots using supercavitating propellers and inverted V foils. In the United States Christopher Hook produced a number of Hydrofin craft featuring mechanical arms used to feel the sea conditions ahead of the craft and thus actuate control surfaces accordingly. During 1958 the US Navy built the Sea Leg followed by High Point PC(H)-1 which achieved 42 knots. Grumman entered the field by building the Dolphin, a commercial hydrofoil, quickly followed by Flagstaff I and by the improved version, Flagstaff II. Boeing, by using their knowledge of aerofoils produced the Tucumcari class. These were followed by a squadron of Sparviero built under a form of licence and or agreement by CNR of Italy. Boeing again commenced the construction of a number of fully submerged hydrofoils for the US Navy, a class known as Patrol Hydrofoil Missile (PHM). In addition they have produced a number of commercial hydrofoils of the Jetfoil class.

Sii then interest in hydrofoil development has fided and Rodriquez has remained the sole producer of hydrofoils apart from the Russian block which has produced its own development line.

Recently hydrofoils have come to the interest of shipyards, operators and Navies, as a means of achieving high speed with limited installed power, as well as offering a superior level of comfort during heavy sea passages. The aged Jetfoil design has been revamped by Kawasaki who under Boeing licence is proposing their product to the commercial market. In the same manner Far East Jetfoils have built a number of Jetfoil derivatives in mainland China to be used on their routes to Macao. Fijellstrand is reported to have sold a number of fully submerged hydrofoil craft based on their catamaran hull to a Hong Kong operator. Even if this is considered something of a novelty it is worth noting that twin hulls and foils were considered during 1960 by Southern Hydrofoils Limited based in Southampton with their Sea Ranger and Ocean Ranger designs. More recently, or more accurately in the near future, an ambitious plan to built a 1000 tons payload hybrid hydrofoil is being carried out in Japan by a number of yards among them Kawasaki, Hitachi and others under the Techno Superliner programme.

Far from being complete this short summary on hydrofoil activity is intended to indicate that the field is an open one with a lot more activity to come in the future.

A1.6.2 General Description

A1.6.2.1 Surface Piercing Hydrofoil

It is interesting to note that in spite of the fact that hydrofoils started their existence operating in the fully submerged mode, this configuration has not been the more popular. In fact the Surface Piercing Hydrofoil (SPH) type has been used in many more designs than the fully submerged form.

As the name suggests the surface piercing type denotes a foil configuration built in such a way that while cruising at the designed speed, a portion of the foil intersects the water surface so operating, in the water/air boundary. More precisely such a foil presents a variable surface area to the water from which it has to obtain its lift.

The foil system has to produce a lift equal to the weight of the craft to which it is attached. In the equilibrium flying condition, the following formula applies

$$W = L \qquad [1]$$

where

W = Overall weight
L = Lift produced

In addition the following applies

$$L = \tfrac{1}{2}.\rho.V^2.A_p.Cl \qquad [2]$$

where

ρ = Water density
V = Relative speed
A_p = Surface projected area
Cl = Lift coefficient

The Lift coefficient, Cl, depends on the foil profiie type, on its chord, thickness ratio etc. as well as on its angle of attack.

Vertical stability, ie. the capability to maintain a fixed flying height, is assured by control of the variable A_p. As soon as the immersion is increased then A_p will increase thus increasing L, and restoring the previous flying height. Surface piercing foils offer vertical stability as well as a self righting capability and are termed inherently stable. This behaviour results in a cost penalty in that the foil system is coupled to the water surface roughness. This means that the ride in heavy seas can be quite bumpy if no countermeasures have been taken during the design of the foil system.

A1.6.2.2 Fully Submerged Hydrofoil

In contrast the Fully Submerged Hydrofoil (FSH) never intersects the water surface, except by accident, and so their immersed surface area never changes. From formula [2] it is clear that since A_p is constant no lift variation can be expected as a consequence of any changes of immersion. Effectively a fully submerged foil system has no vertical stability at all ignoring a small amount produced as a result of the minute changes in Cl occurring as a result of the depth of immersi'on variation. Furthermore such a configuration has no lateral stability whatsoever and a form of outside control is needed to keep them on the correct flying trajectory. They are therefore classed as being inherently unstable.

Si the flight of such a foil system is independent of variations in it's immersion it is almost completely decoupled from the sea surface. No matter how rough the sea is, the submerged foil craft will have very low motions. This requires the vessel to have the capability to take-off in rough seas and is only limited when waves impact with the hull of the vessel.

A1.6.3 Fundamental Features

A1.6.3.1 Hullform

Apart from very few designs, hydrofoil craft of both surface piercing and fully submerged types, are based on the monohull type. Hull material is light alloy, either welded or rivetted, while foils are made of steel. The choice between a rivetted or welded hull depends upon many factors, one of which is the available technology at the point of manufacture or in the operating area.

Hydrofoils are intended to fly with their hulls well above the water and so the hull smoothness is not of paramount importance. This is because the hull stays in the water for only a limited amount of time and normally at relatively low speeds.

Rodriquez built surface piercing hydrofoils have always been wholly rivetted enabling the use of small thickness plates in the hull as well as simplifying repairs in geographic areas where light alloy welding can be a problem. On the other hand fully submerged hydrofoil craft have welded hulls as their take-off. speed is quite high and so they operate hull borne at speeds where hull smoothness can be of considerable influence to the overall drag.

A1.6.3.2 Stability

The cases in which the hydrofoil craft is in the hullborne and in the foilborne modes must be considered. Hullborne mode is, as the word suggest, when the craft is at standstill or at a speed too low for the foils to exert tbeir lifting action. Foilborne mode is achieved when the hull is well above the water and stability forces depend exclusively on the foil configuration.

Fully submerged hydrofoil craft normally shows quite poor hullbome stability inasmuch as the weight of the foil system is unable to compensate for the weight of the hull and superstructure. Surface piercing hydrofoils have superior hullborne stability thanks to the fairly big foil structure which shifts the centre of gravity downwards.

A1.6.3.3 Longitudinal Stability

Longitudinal stabiity ie. the ability to avoid high pitch angles is very poor for fully submerged hydrofoils as such a foil configuration is very insensitive to immersion changes. The opposite is the case when the surface piercing configuration is used. This latter system has a tendency to follow the wave contour thus imposing vertical accelerations on the craft. We can then say that fully submerged hydrofoils show a tendency towards platforming while surface piercing hydrofoils shows a tendency to contouring. Contouring is defined as being when the craft vertical motion describe a path equal to the wave profile. Platforming is said to occur when the craft is travelling on a level path over the waves. Unfortunately neither behaviour is particularly desirable and so additional devices need to be installed to allow the FSH to perform limited contouring and the SPH to perform some platforming.

A1.6.3.4 Transverse Stability

Transverse stability of a foilborne FSH is very poor as no changes in lift can be produced by the two lateral portions of the foils. Lift changes cannot be expected as a result of immersion variations. On the other hand such a change in lift is the reason for the existence of the SPH. Lift variation is a result of both the changes in foil wetted surface area as well as from the variation of foil depth itself.

A1.6.3.5 Range of Operating Speed

It can be demonstrated that the relation between the take off speed of an SPH and an equivalent FSH is described by

$$V_{FSH} = 1.414 . V_{SPH} \qquad [3]$$

where

V_{FSH} = Take of speed for FSH
V_{SPH} = Take of speed for SPH

This means that if an SPH takes off at 20 knots, an equivalent FSH will take off at a speed of about 28 knots. To attain 28 knots in hullborne mode an appropriate level of power will be needed. This is even more true in higher sea states. The power/speed curves for both foil configurations shows a hump at the take off boundary. The effects of such a hump are more evident with an increase in the designed cruising speed. The high power needed by an FSH to overcome the take off resistance is then available to speed up the craft to a higher cruising speed. As such a requirement is not present for the SPH their top speed is normally lower than that of their FSH counterpart.

A1.6.4 Layout Arrangements

A1.6.4.1 Accommodation

Layout of both FSH and SPH is conventional. Usually two decks are present with a wheel house on top. On commercial vessels available area is used to accommodate passengers seated in rows of aircraft type seats. On some craft the lower area or saloon has been used for cabins for crew and personnel.

In a number of designs intended for military use the lower spaces have been devoted to living quarters for the crew while the upper spaces have been used for command and control centres and to accommodate all the equipment required for the craft to fulfil its military role.

A1.6.4.2 <u>Deck Spaces</u>

Deck spaces are available fore and aft of the superstructure. The amount of space depends on the length of the superstructure and is a trade-off between the need for volume and the available gross deck area. Usually there is enough room left at the bow to fit the required mooring equipment. On commercial hydrofoils the aft deck spaces are usually used to store luggage while on a military hydrofoil it can be used for various purposes including

- Missile canister
- Torpedo launcher
- Sonar deployment equipment

A1.6.4.3 <u>Machinery</u>

Machinery spaces can be of two types depending on the layout of the craft or often on the foil configuration which has been chosen.

- **On board maintainable**
- **Base maintainable**

Usually since SPH are used in the commercial field they need to be more reliable and less expensive to run than their military counterparts. This imposes the requirement to have access spaces around the engines in order to inspect and maintain them even when underway. In contrast FSH intended for military applications, where space is at premium, have tight engine rooms with very limited or no access resembling aircraft installations where engines are maintained only at the base.

The locations of the engine room vary according to the same philosophy. SPH have the machinery space at mid-length of the ship. This is enforced by the very simple Engine/Reversing-gear/Shaft/ Propeller arrangement these vessels have. FSH with their gas turbine-water jet systems pack all the machinery at the extreme aft of the vessel. This arrangement places the centre of gravity well aft in the hull and so the hull form should take this into account.

A1.6.5 <u>Resistance and Powering</u>

A1.6.5.1 <u>Resistance</u>

As described in section A1.6.4.3 the hydrofoil is unconventional in that at cruising speed it doesn't rely on buoyancy forces on the hull but the hydrodynamic lift developed by the foils under the water surface. A diagram of the total resistance vs. speed is showed in figure Al .6.1.

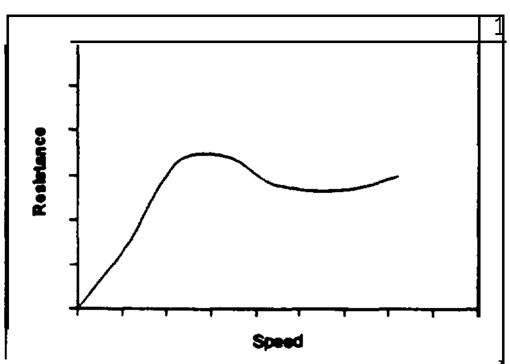

Figure A1.6.1
Resistance Curve for Hydrofoil Craft

The curve shows

Hullbome mode

Transition region
The hydrofoil is in a condition whereby the hull is partially supported by buoyancy and partly by the lift produced by the foils.

Foilborne mode
The lift produced by the foils is sufficient to support the weight of the craft.

The components of resistance of the first two regions are very similar to those of a conventional hull except that the component of appendage resistance due to the foils, the support structure etc. is considerable.

However in the foilborne mode the resistance to motion is due only to the immersed components, foils and support structures, and is due in part to the viscosity of the fluid. This component of resistance can be expressed in terms of a resistance coefficient Cd as follows

$$D = \tfrac{1}{2}.\rho.V^2.S.Cd \qquad [4]$$

where

ρ	=	Density of water
S	=	Foil surface area
V	=	craft speed
Cd	=	Drag coefficient dependent on angle of incidence and foil geometry

To a first approximation

$$Cd = Cd0.Alpha \qquad [5]$$

$$Cd0 = 2.Cf.(1+1.2t/c)+0.11.(Cl-Cli)^2 \qquad [6]$$

$$Cf = 0.032.(k/c)^{0.2} \qquad [7]$$

where

Alpha	=	Angle of incidence measured from the angle for which the lift is zero
t	=	Thickness of the foil
c	=	Chord of the foil
Cl	=	Lift coefficient defined in analogous manner to resistance coefficient
Cli	=	Ideal lift coefficient
k	=	Average height of the foil roughness

The resistance component considered thus far is due to the fluid viscosity. There are also other resistance components caused by the following phenomena

Effect of the free surface
In a finite fluid the pressure drop that is created on the upper part of the foil not only lifts the same foil but acts on the free surface of the water causing a loss of lift, a wave formation and thus a wave resistance.

Finite foil span
In exactly the same manner as happens for the wings of aeroplanes, the foil of a hydrofoil, being of finite span, is affected by loss of lift and induced resistance caused by the three-dimensional flow of the wake vortex system. **However such losses are partly recovered** by the support struts that act as end plates and render the flow more two dimensional.

Effect of support struts
The resistance of the struts has three components

- Resistance of section (equation [6])
- Interference with the foil joint
- Resistance created from spray at the surface

The aforementioned elements are relevant in calm seas or in the presence of waves that do not reach the hull. In the case of very rough seas with waves that do not allow foilborne navigation, the craft can move in hullborne **mode,** at a reduced speed, in the same manner as a conventional craft.

A1.6.5.2 Propulsion

Hydrofoil craft can adopt a variety of propulsion system configurations depending on the type of foil system. Generally there are the following options

- **Diesel engines coupled** to **marine propeller**
- **Gas turbine coupled to marine propeller**
- Gas turbine coupled to water jet

SPH are generally propelled by diesels and marine propellers while FSH generally have gas turbines coupled to water jets. Either propulsion system has advantages and disadvantages.

Conventional non supercavitating propellers show a much better efficiency than waterjets at low speeds up to 35 knots, above which the advantages of a well designed waterjet system become more evident. If the hydrofoii has to cruise at a speed near this transition speed then the use of a conventional propeller is preferred. This **is the case** if the craft has to be used for patrol purposes and thus spends most of its time at low speed. It will thus be a waste of fuel to use an inefficient waterjet. In the event that the mission profile demands a speed over 40 knots the solution is a supercavitating propeller or a waterjet as the more conventional propeller would be operating at its operational limit.

With regard to the engine, the use of either diesels or gas turbines show a number of pros and cons. Diesels are well known to the seafarer and are simple to maintain. However they are bulky and heavy when compared to a gas turbine of the same power. This weight difference is balanced by the extra fuel the craft has to carry because of the increased specific fuel consumption (sfc) of a gas turbine compared to a diesel engine. State of the art diesels show an sfc of about 213g/kW/h while the equivalent figure for a gas turbine can be in the range 300-380. This difference would be reflected in the size of the fuel tank as well as in the fuel bii for a patrol craft, whose mission is to stay at sea for a particular amount of time. This difference tends to reduce when high power gas turbines are considered. However these would be well outside the range of typical hydrofoil installations where the total power requirement is generally in the range of 4000 to 8000 kW.

A 1 . 6 . 6 Seakeeping

There are a number of issues to be considered

Flight control system
Fully submerged hydrofoils need a Flight Control System (PCS).

Seakeeping Augmentation Contrdller
Surface piercing hydrofoii may have a Seakeeping Augmentation Controller (SAC) installed **although this is** not essential.

Craft complexity
Complexity and thus cost differences between the two types of hydrofoils are an important consideration when designing systems.

As stated previously a FSH has to rely on some form of control system in order to keep it in flight. Such a control system is **nowadays built** using either analogue or digital electronic technology. The FCS senses, by means of a number of sensors, the actual flight path, compares it with that desired and controls movable surfaces, namely **flaps,** situated on the trailing edges of the foils so as to exert the necessary restoring forces and moments needed to keep the hydrofoil craft stable. As FSH rely completely on such systems for **their survivability** the FCS is normally of dual redundant **configuration,** having a large number of its components duplicated or even triplicated. In the latter cases a special logic is built in using a majority voting system to ensure **continued** safe operation.

SPH are inherently stable and thus there **is no need to** incorporate a control system. The only reason for the **presence** of **such** a system **is the** fact that a higher degree of comfort is generally required nowadays. It is interesting to note that this is the reason why the electronics system fitted on SPH and supplied by Rodriquez is known as a Seakeeping Augmentation Controller. SPH seakeeping behaviour in rough seas has been dramatically improved by the use of such systems to the extent that commercial voyages in sea state 6 and at **full** cruising speed are feasible. When compared with other types of conventional or even unconventional craft, such as monohulls and catamarans, the sea-keeping of both FSH and SPH is far superior. **This** has been proved by a number of sea trials during which neither crew nor passengers **suffered fatigue** or **seasickness.** This is not only true when the SPH is in the foilborne mode but also when operating in the hullborne mode as the foil structure acts to damp out the motions.

A 1 . 6 . 7 Structures

A1.6.7.1 Structural Design

Strength **calculations for** hydrofoils **need** to consider the distribution of the craft weights, the location and the **form** of the **foils,** the propulsion thrust and any accelerations in the presence of rough seas. Loading **cases should account for transverse** and longitudinal loads with particular regard to the transitional phases **of take off and landing on water and during turns.**

In general the structures of hydrofoils are predominantly of longitudinal framed configuration because of **the need for** simplicity of **construction** and **lightness.** At the extreme bow and stem structures of transverse **framed form are used in order to provide adequate strength to** resist collision damage. The material used in the majority of cases is **aluminium,** with joints either welded or rivetted.

Just as for conventional craft the structural calculation **should** consider the following

A1.6.7.2 **Longitudinal Strength**

Load cases should consider both hullborne and foilborne modes in calm water and in rough seas.

During navigation in calm water the hull is in equilibrium between its weight and the hydrodynamic lift of the foils, while in rough sea conditions inertial forces due to vertical accelerations should also be considered. An experimentally derived formula for the acceleration at the centre of gravity at a 1% exceedance level is as follows

$$a_{cg} = 0.65.(0.2+0.6/V_{rel}).V_{rel} \qquad [8]$$

where

a_{cg} = Acceleration at c.g. (g)

V_{rel} = Relative speed (knots)

This equation is applicable for open sea conditions with $h_{1/10}$ significant waves of 4 m. The result must be lower than lg. Once the acceleration at the centre of gravity is known the longitudinal distribution can be derived by means of suitable corrective coefficients.

A1.6.7.3 **Local Loads**

The structure of the hull must be designed with regard to the impact of the water during the landing phase and other local loads such as engines, lift from the foils acting through the struts on the huh, loads on the deck etc. The stresses resulting from such loads must be added to those derived from the longitudinal strength calculations taking into account tbe most unfavourable but realistic combination.

A1.6.7.4 **Local Strength**

Hydrofoils of both configurations are of conventional form as far as their hull design is concerned and so normal design calculations are carried out following the relevant Classification Society rules. Departure from those rules is necessary in order to take into account the fact that being a flying object the hull, when foilborne, is supported at only two locations, namely at the bow and the aft foils. In these areas local reinforcement is needed in order to accommodate the foil mounting loads.

A1.6.8 **Weights**

In the construction of a hydrofoil special attention must be paid to weight control. In this respect the design of hydrofoii is similar to that of aeroplanes. In the case of other types of fast craft such as monohulls or catamarans, an undesired increase in weight will result in a cruising speed lower than that designed. However in tbe case of the hydrofoil weight increase could result in the thrust required for take-off being higher than is available from the propellers.

A1.6.9 **Survivability**

This is composed of both susceptibility and vulnerability.

A1.6.9.1 **Susceptibility**

the underwater signature of both FSH and SPH differs very much from that of a conventional monohull or from that of a catamaran for a number of different reasons

- **Presence of a foil** system
- **Absence** of the radiated noise from the machinery

A1.6.9.2 **Vulnerability**

A hydrofoil is a flying object and as such the hull, while foilbome, is well out of the water. in such a condition what is not in the water cannot he damaged by underwater weapons. However, when above water the hull is susceptible to damage by gunfire and missile.

A1.6.10 State of Technology

Hydrofoil craft technology is a field which does not need to be investigated from scratch as most of the knowledge and necessary tools have already been developed, and to a certain extent, implemented. Of course a more refined toolset to avoid costly sea trials and/or trial and error iterations during the design phase would be very welcome. This seems not to be a problem as computer science is improving and computer power is increasing everyday.

An open area is the integration of all the elements of hydrofoil knowledge so as to obtain the optimum design which would fulfil the required tasks.

A1.6.11 Advantages and Disadvantages

The fundamental advantages of the hydrofoil in comparison to other types of fast vessel of the same size and installed power are the higher cruising speed and the higher level of comfort. In addition the high speed and comfort of the hydrofoils is hardly affected by waves up to the point at which sea conditions prevent foilborne navigation. Even in very rough seas, and in all the other circumstances that impose hullborne operation, the presence of the immersed foils will give the craft a high stability and appreciable reduction of vertical motions. For example, model tests have demonstrated that a 200 tons hydrofoil could show roll and pitch motions comparable to those of a conventional vessel of 5000 tons due to the damping action of the foils.

The principal disadvantage of the hydrofoil is the limited payload capability and the impossibility of increasing this beyond a certain limit in a manner that is economically acceptable. This is because as the installed power required for take off goes beyond a certain limit it is necessary to use gas turbine propulsion in order to save weight while other types of craft can still use diesel engines. A possible solution to this problem is the division of the installed power into units each of which has a good power to weight ratio. However with the present state of the art it is difficult to envisage such a transmission system.

Al.6.12 **Concluding Remarks**

For high speed operation with a light payload hydrofoils offer many advantages. For high performance applications the high level of technology and hence support costs can be a problem. ‘The technology is well understood and many craft are in service.

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ANNEX 2.0 - DESIGN CHARTS

The purpose of this annex is to provide design charts that can be used to provide an initial comparison between three different hull types for a wide range of performance requirements.

The craft types considered are:

- **Monohull**
- SES
- **SWATH**

The performance requirements considered are:

- **Designspeed**
- **Range**
- Payload weight

Results are presented in terms of:

- Full load displacement
- **Relative cost**
- **Seakeeping performance.**

A2.1 INTRODUCTION

As part of an IEG/6 group continued assessment of alternative craft types. A joint co-operative study between the German and Royal Netherlands Navies has been undertaken, to assess the relative merits and costs of monohulls, SES and SWATH in various roles.

The study covered the following requirements:

- **Design speed**
  20 to 55 kn (5 kn steps) with a fixed cruise speed of 18 kn.

- Range
  500 to 4500 nm (500 nm steps) with a fixed endurance of 10 days.

- Military payloads
  40.75 and 90 t.

Craft outlii designs were prepared to satisfy each combination of requirements, using existing generic design synthesis computer programs. Restrictions were introduced to control practical speed limits, for example the maximum speed of monohulls and SWATH vessels was assumed to 'be 40 knots.
The seakeeping of each new design was assessed and its limiting wave height determined. This was controlled by either the bow acceleration level not exceeding 0.55g or the pitch motion not exceeding 0.3 degrees (sig. Values in head sea operations). Central North Sea statistics (Grid Point 7 acc. To STANAG 4194) were considered. Involuntary speed reduction due to added resistance was also taken into account.

A common set of costing algorithms was used to estimate the acquisition cost exclusive of payload cost for each vessel. These included assumptions regarding the design and logistic support costs. The average unit production cost (10 off) of each design was then compared to a common baseline represented by a monohull carrying a 75t payload with a design speed of 30 knots and a range of 2500 nm.

The form of the study is shown in figure A2.1

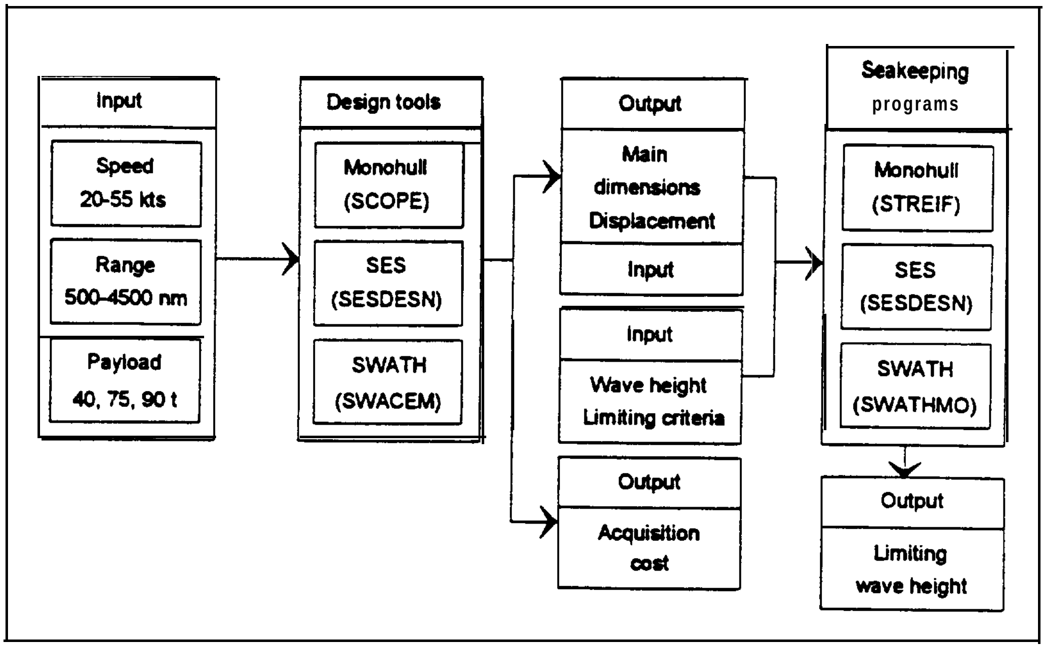


Figure A2.1: Parametric Design Study for Monohull, SES and SWATH

The investigations were undertaken jointly by MTG Marinetechnik on behalf of the German Navy and by DMKM Schebo on behalf of the Royal Netherlands Navy.

A2.2 BACKGROUND

A2.2.1 Payload Definitions

Baseline 40t payload included:

- Radar systems and communications
- Guns, Harpoon, RAM and Chaff
- Ammunition and Stores

Increased 75t payload added:

- CIWS, UAV and ammunition

Increased 90t payload added:

- UAV replaced by helicopter plus helo fuel.

A2.2.2. **Manning Levels**

A common algorithm based on the vessel's full load displacement and range together with a separate crew allowance for the weapon system and helicopter was used to derive total crew numbers. This typically gave a value of about 65 crew on a 1500 t vessel.

A2.2.3 Hullform and Construction

Each vessel was designed for the stated requirements and did not depend on a common hullform. In the case of the SES sufficient wetdeck clearance was maintained so that the craft could operate satisfactorily in the fully afloat mode at the 18kn cruise condition.

All vessels were assumed to be constructed with steel hulls and superstructures. For the 90t payload case a helicopter deck was arranged aft.

A2.2.4 Propulsion Systems

Twin controllable pitch propeller propulsion was assumed for all vessels upto a design speed of 40kn. For higher speeds twin waterjet propulsion was assumed for the SES with auxiliary small propellers fitted for the 18kn cruise condition.

Diesel engines were assumed for total installed power requirements of less than 12,000kW. For higher propulsion power levels gas turbines were assumed. For SES the lift system was assumed to be diesel powered, with the abiity to alternatively employ such engines as a means of providing power for the cruise condition.

A2.3 **RESULTS**

A2.3.1 **Monohull**

The variations in the full load displacement of monohulls with changes in design speed (upto 45kn) and range, are shown in Fig A2.2 - A2.4 and in the carpet plot form in Fig A2.5. The corresponding cost ratios in relation to the 75t payload, 30kn, 2500nm range baseline are shown in Fig A2.6 - A2.8 and Fig A2.9. The limiting wave height for each design is also shown on the carpet plots. The 45kn cases have not been considered in the carpet plots because of their unrealisticly high displacements and cost. The applied strip - theory for the monohull seakeeping calculation is not applicable for speeds above 35 knots. Extrapolation of seakeeping performance above this speed is not valid.

A2.3.2 **SES**

The variations in the full load displaament of SES with changes in design speed (upto 55kn) and range, are shown in Fig A2.10 - A2. 12 and in carpet plot form in Fig A2.13. The corresponding cost ratios in relation to the baseline monohull, are shown in Fig A2-14 - A2. 16 and Fig A2.17. The limiting wave height for each design is also shown in each carpet plot.

These plots show discontinuities where propeller propulsion is changed to waterjet at higher speeds. A fairly uniform rise in both the displacement and cost are indicated, with change in requiremenk. Values generally lie between equivalent monohulls and SWATH vessels but indicate advantages with increasing speed.

A2.3.3 SWATH

The variations in the full load displacement of SWATH vessel with changes in design speed (upto 40kn) and range, are shown in Fig A2.18 - A2.20 and in carpet plot form in Fig A2.21. The corresponding cost ratios in relation to the baseline monohull, are shown in Fig A2-22 - A2.24 and Fig A2.25. The limiting wave height for each design is also shown on the carpet plots.

Both the displacement and cost are generally higher than for the equivalent monohulls but are shown to rise more uniformly with payload and range requirements.

A2.4 OVERVIEW OF RESULTS

Clearly the relative merits of each vessel are dependent upon the role requirements. Four examples have been explored, as follows:-

- 20kn design speed with a range of 4000nm (Fig A2.26 - A2.28)
- 30kn design speed with a range of 2500nm (Fig A2.29 - A2.31)
- 40kn design speed with a range of 1500nm (Fig A2.32 - A2.34)
- 40kn design speed with a range of 4000nm (Fig A2.35 - A2.37)

Comparison of the full load displacement, relative cost and limiting wave height for the three types of vessel designed for each requirement are illustrated in Fig A2.26 - A2.37. Clearly for moderate speeds and high range requirements, the monohull will provide the lowest cost solution. Conversely if high speeds are required the SES may be the only solution. Both types of vessel appear to have similar costs at a speed of about 40kn. If good seakeeping is desired then SWATH vessels generally provide the best solution but at an increased cost compared to the monohull.

Fig A2.34 and A2.37 apparently show an advantage at higher speeds in seakeeping for the monohull, but the selected criteria do not allow for bow flare slamming especially in higher sea states which would of course reduce the limiting wave height considerably. Similarly wet deck slamming for the SES has to be considered under these extreme conditions.

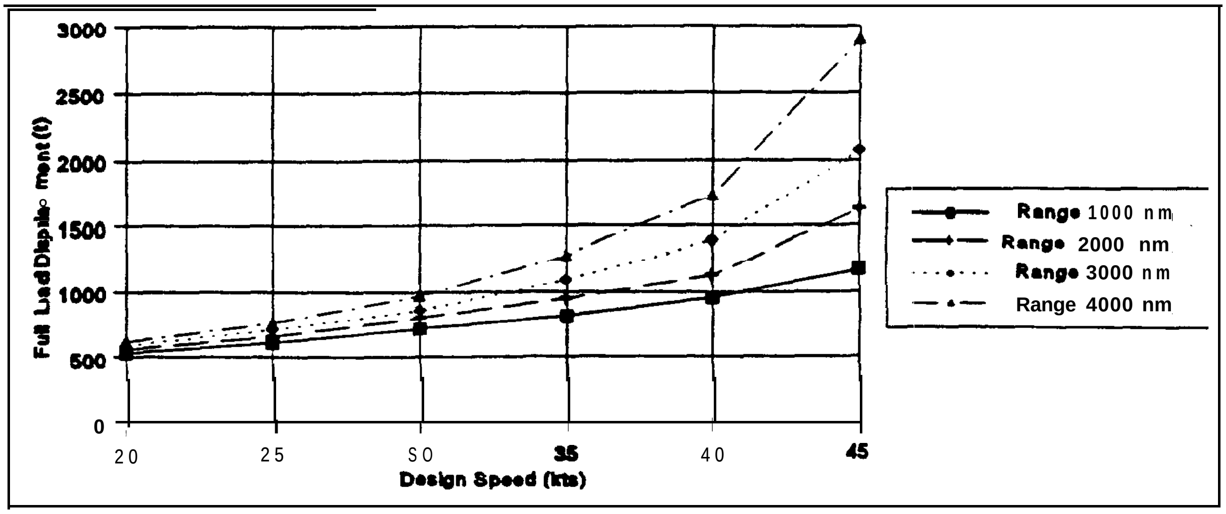


Figure A2.2: **Monohull** Study - Full Load Displacement/Speed - 40t Payload

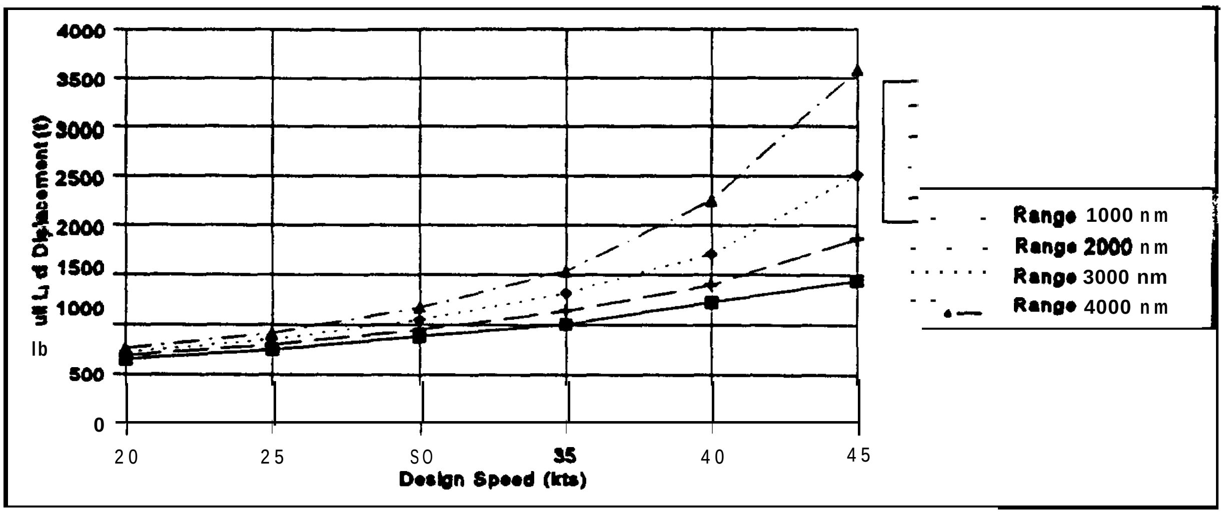


Figure A2.3: **Monohull** Study - Full Load Displacement/Speed - **75t** Payload

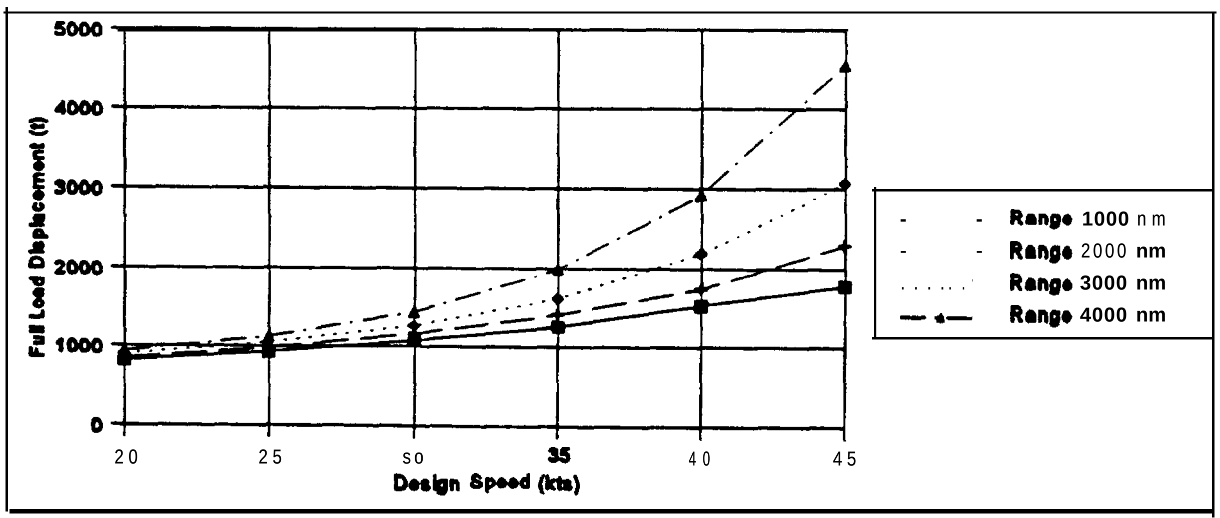


Figure A2.4: **Monohull** Study - Full Load **Displacement/Speed** - 90t Payload

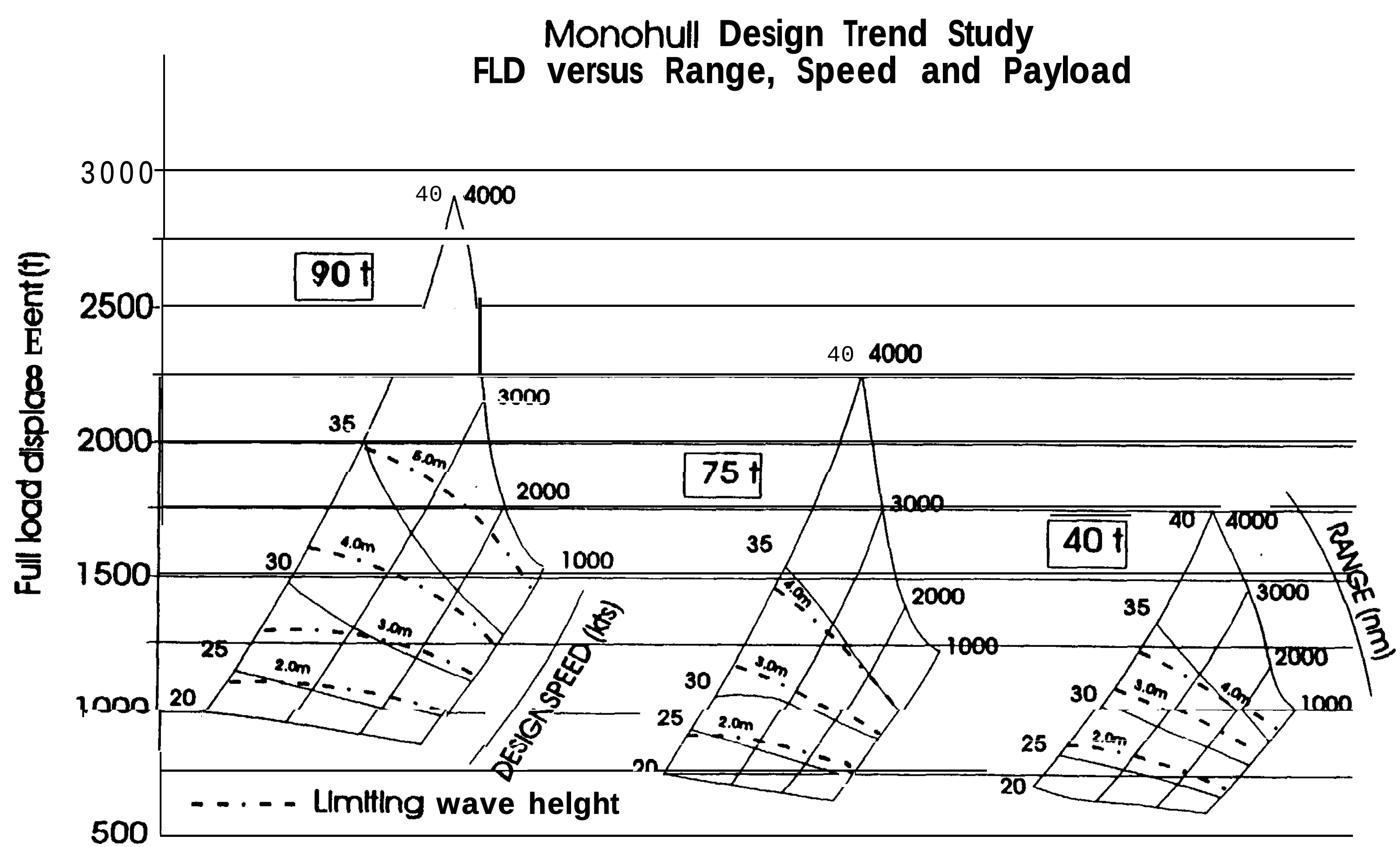


Figure A2.5: Monohull Design Study Results - Full Load Displacement

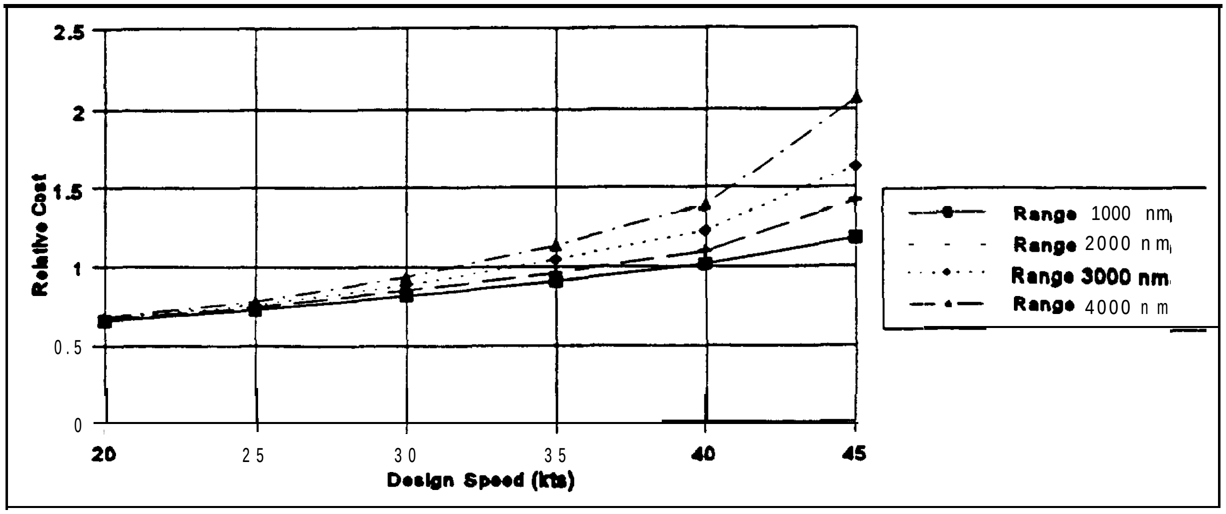


Figure A2.6: **Monohull** Study - Relative Cost/Speed - **40t** Payload

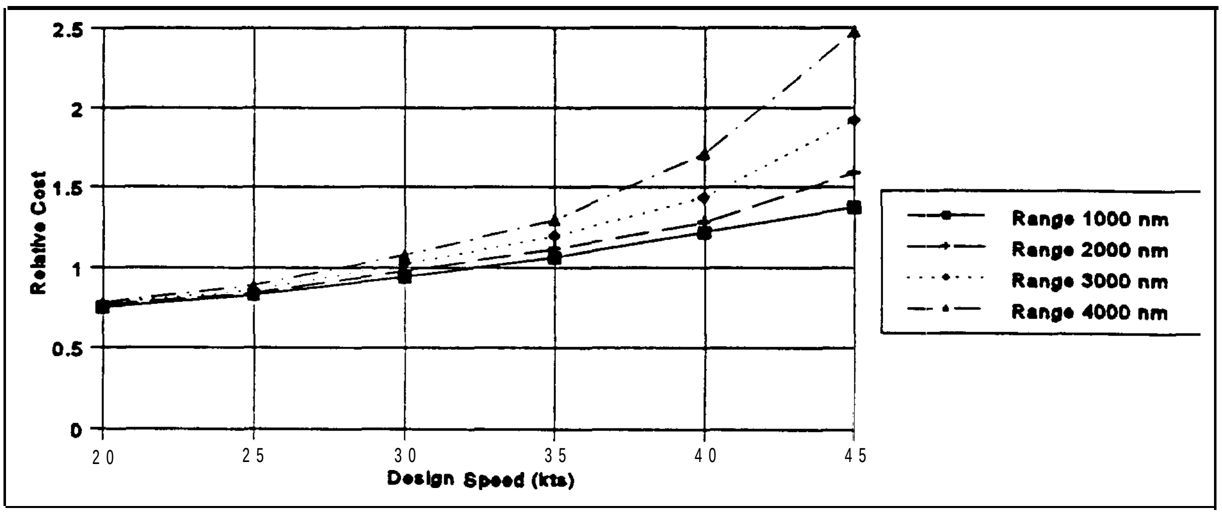


Figure A2.7: **Monohull** Study - Relative Cost/Speed - **75t** Payload

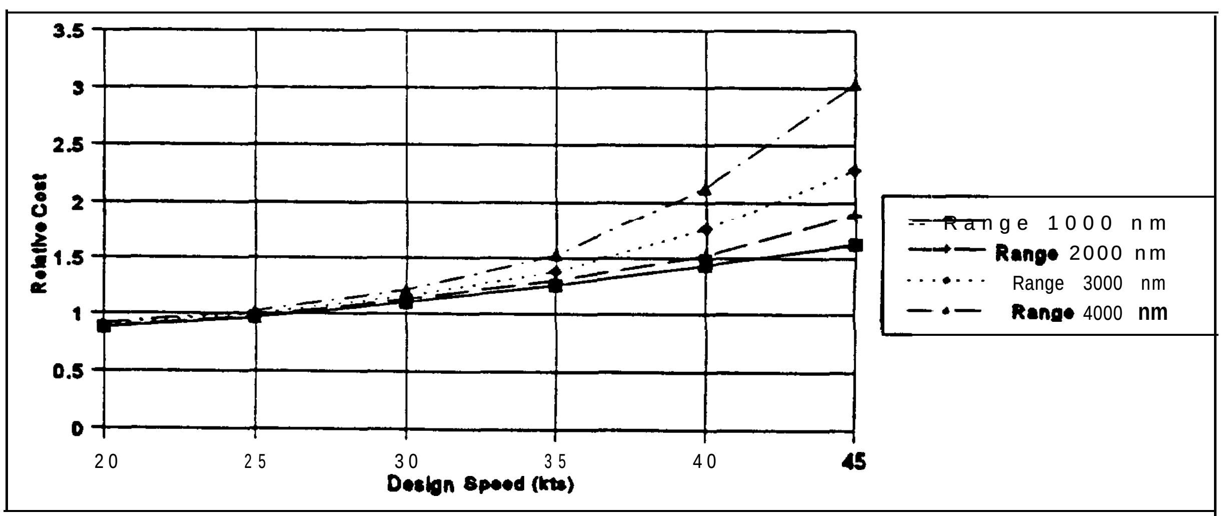


Figure A2.8: **Monohull** Study - Relative Cost/Speed - **90t** Payload

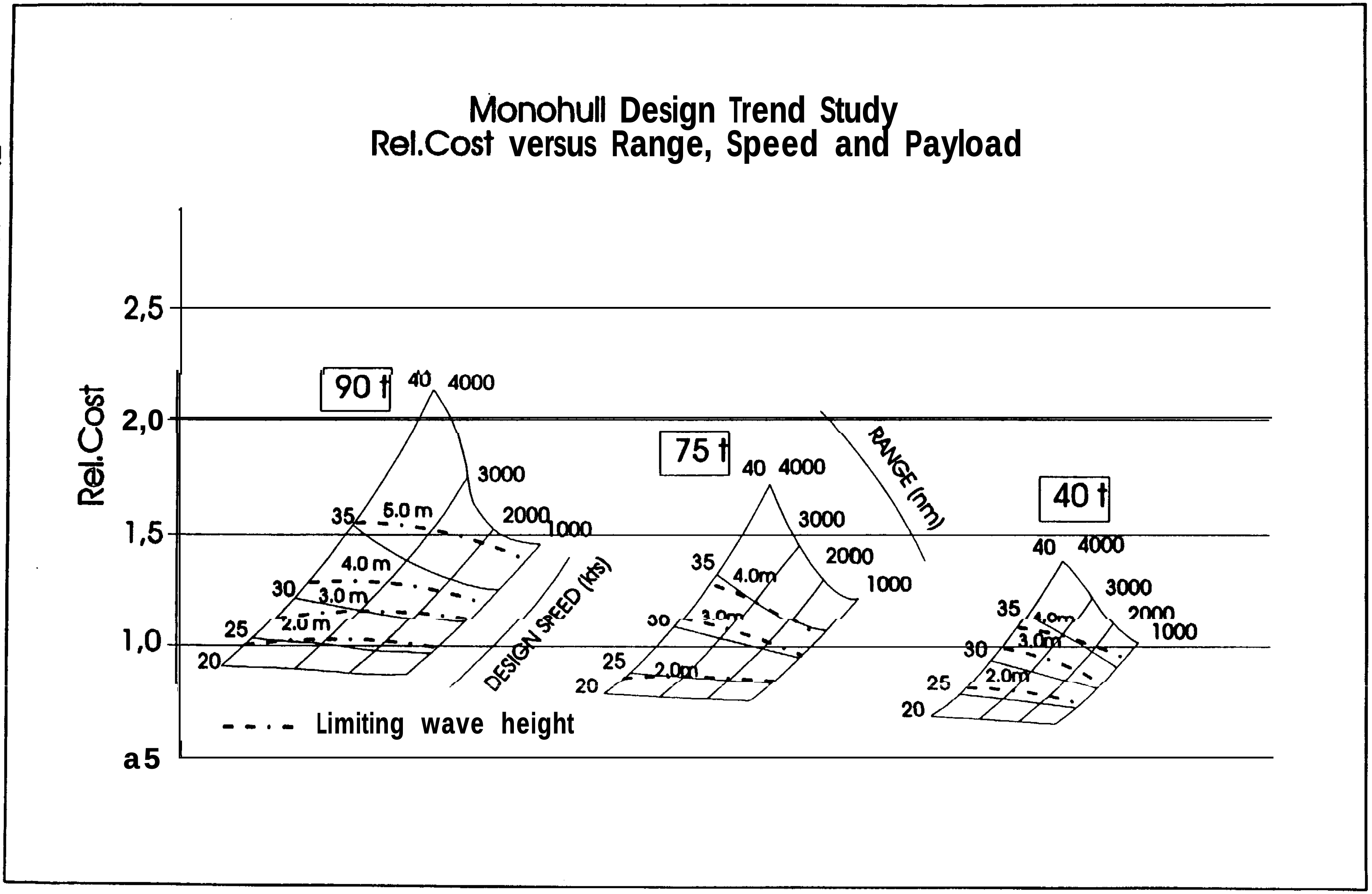


Figure A2.9: Monohull Design Study Results - Relative Cost

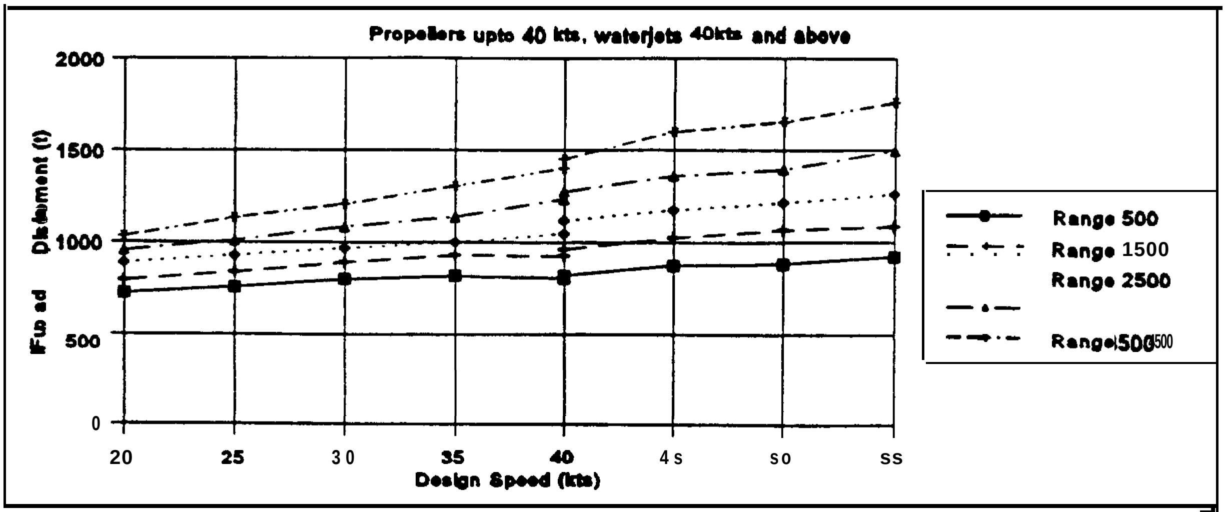


Figure A2.10: SES Study - Full Load Displacement/Speed - 40t Payload

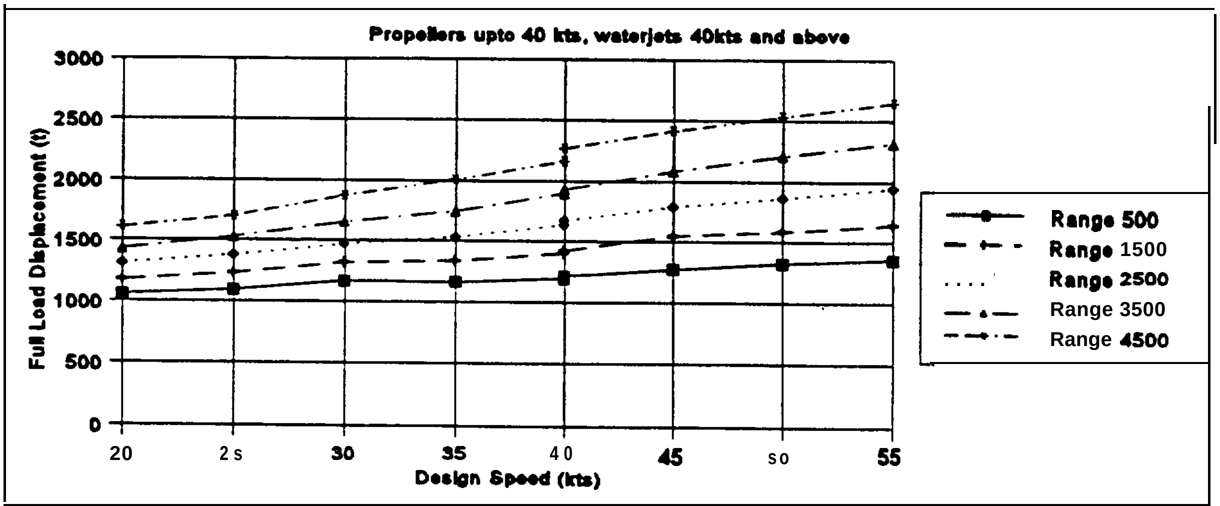


Figure A2.11: SES Study - Full Load Displacement/Speed - 75t Payload

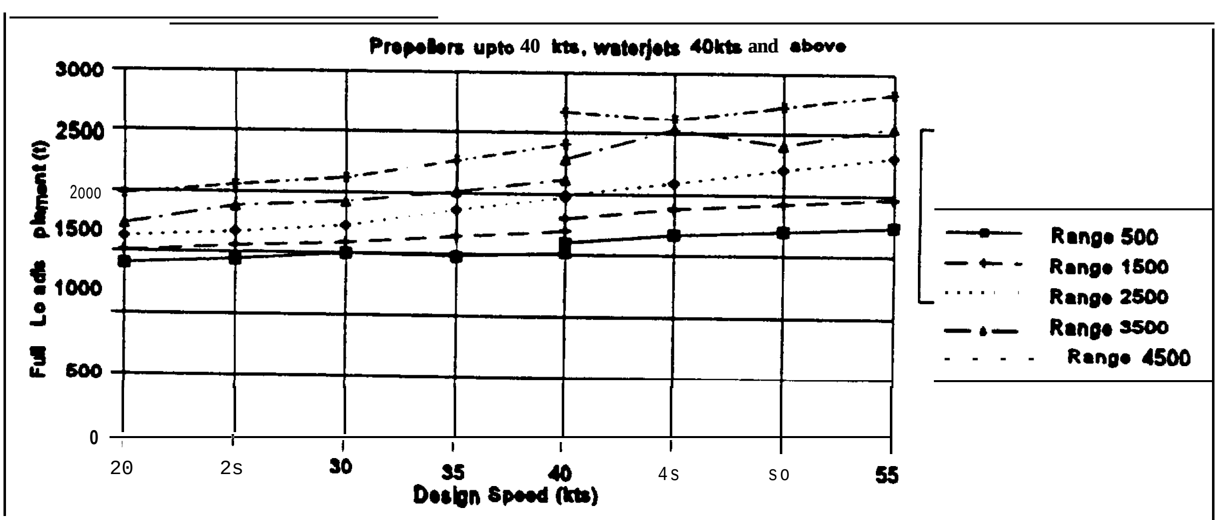


Figure A2.12: SES Study - Full Load Displacement/Speed - 90t Payload

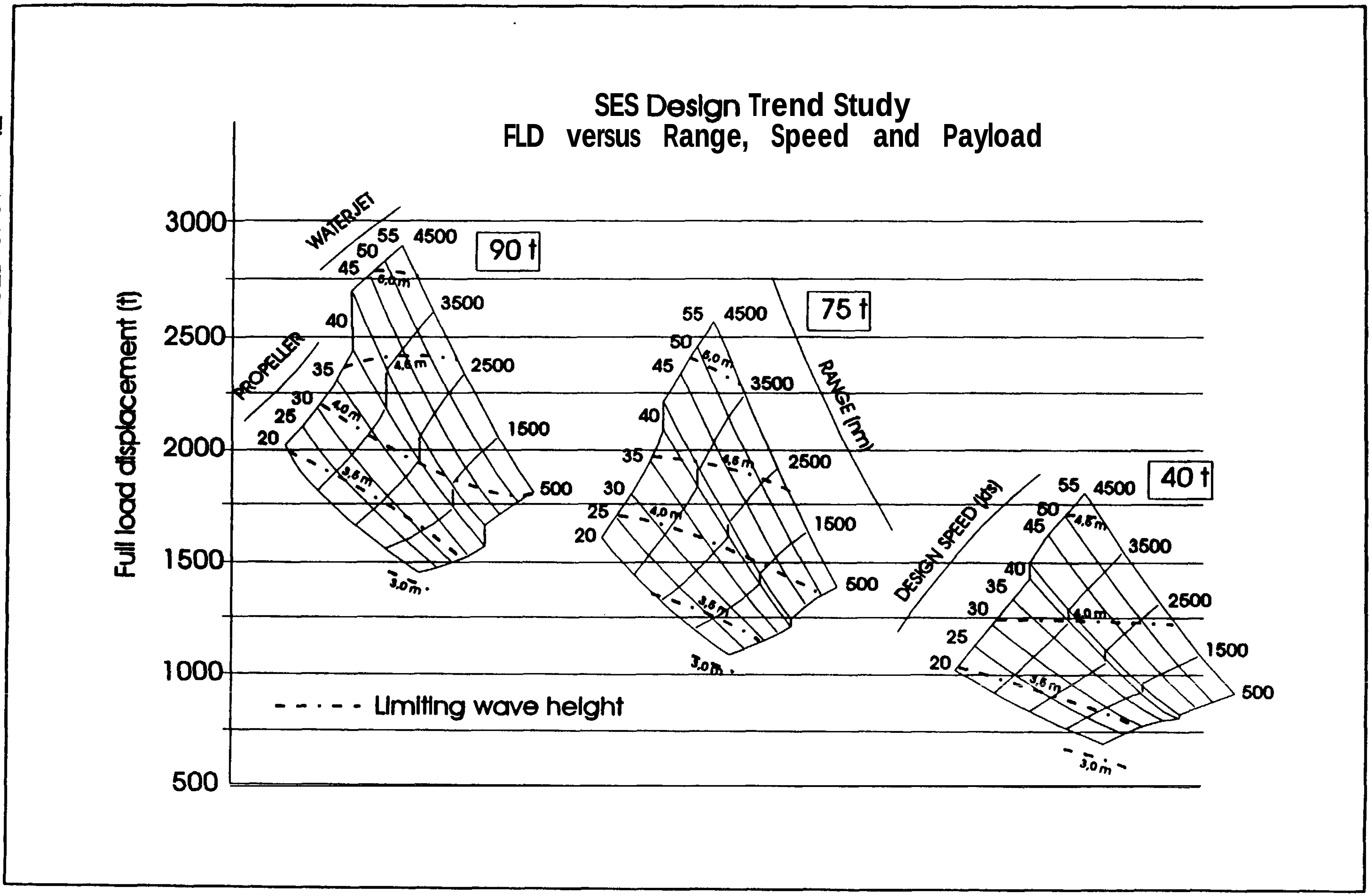


Figure A2.13: SES Design Study Results - Full Load Displacement

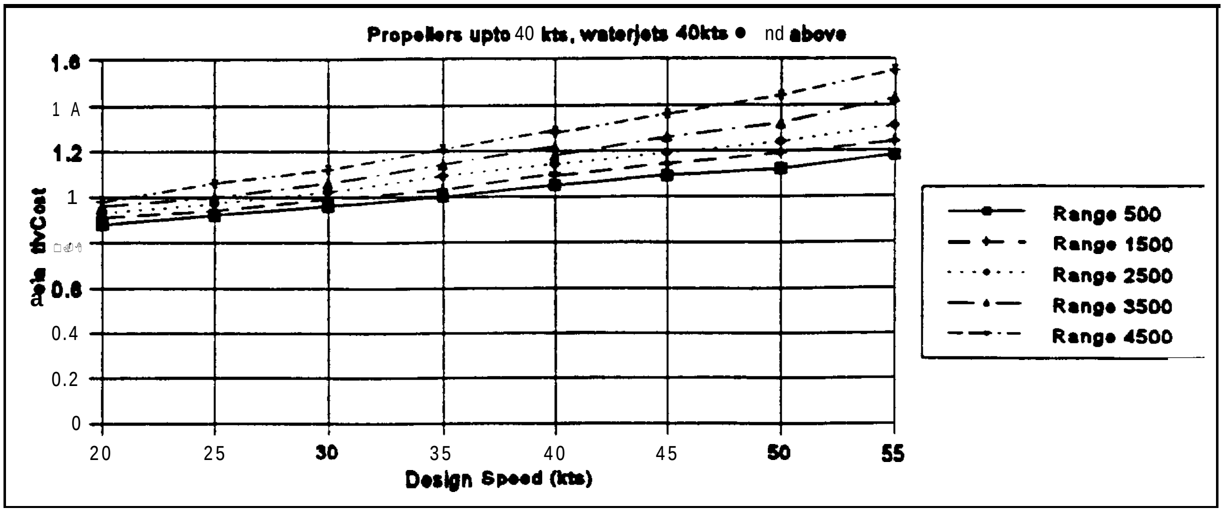


Figure A2.14: SES Study - Relative Cost/Speed - 40t Payload

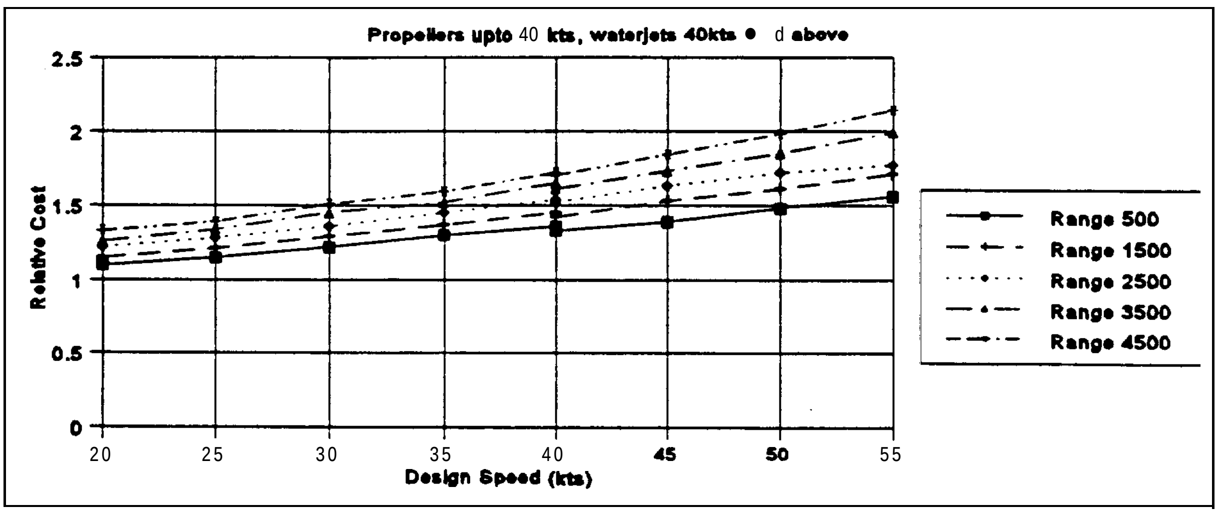


Figure A2.15: SES Study - Relative Cost/Speed - 75t Payload

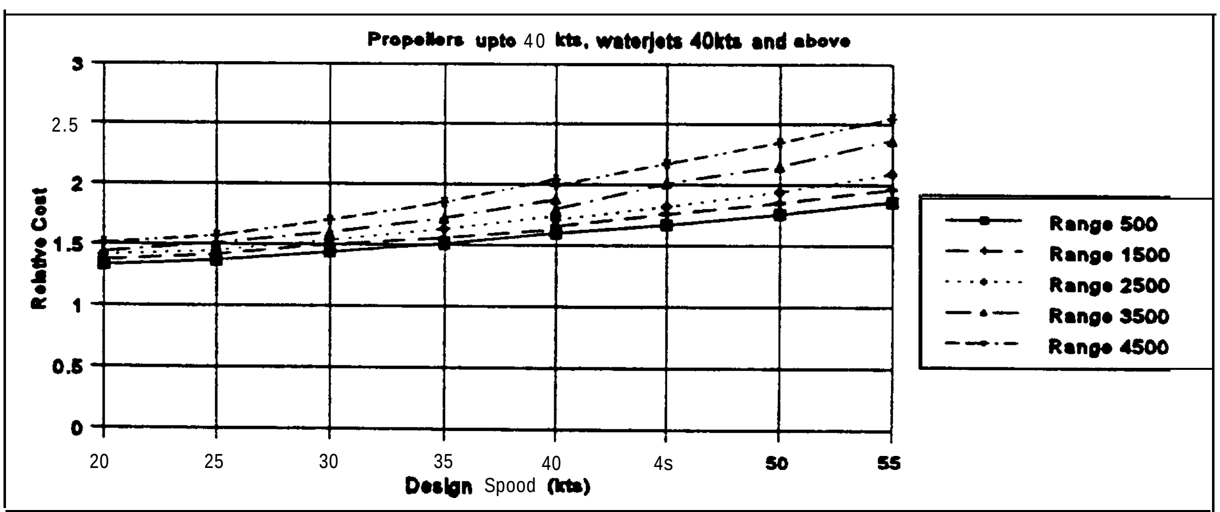


Figure A2.16: SES Study - Relative Cost/Speed - 90t Payload

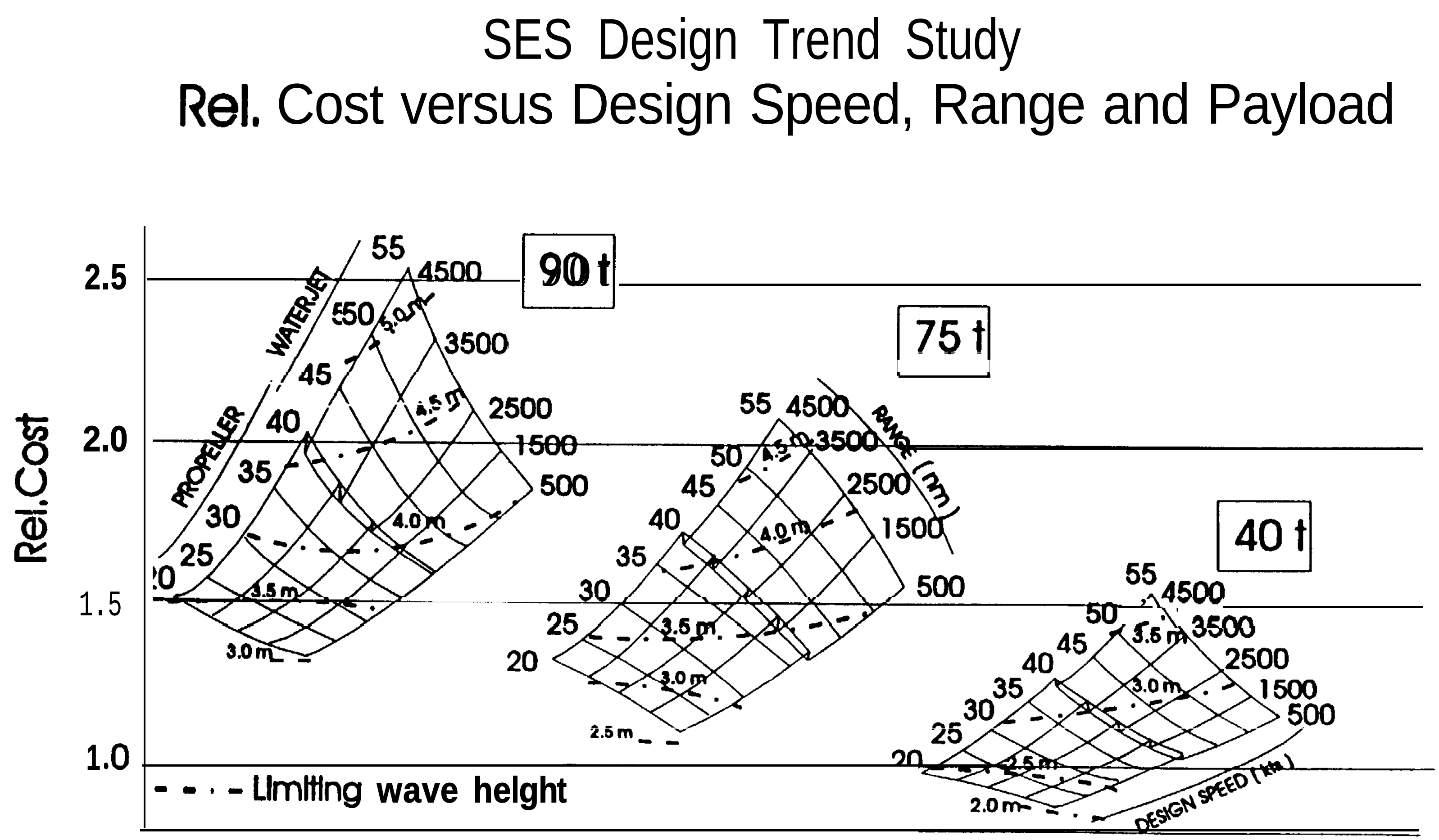


Figure A2.17: SES Design Study Results - Relative Cost

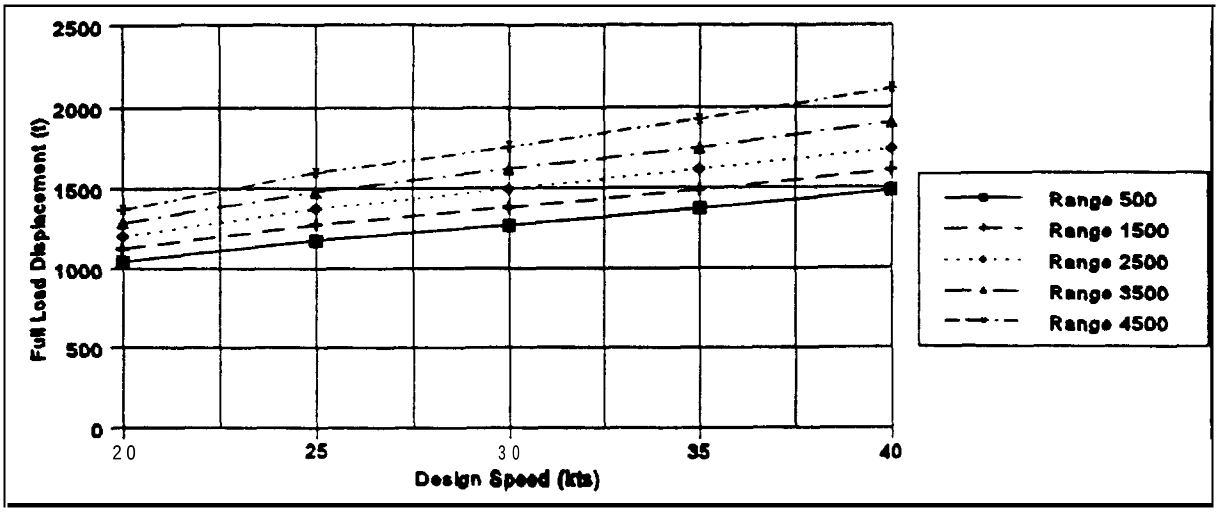


Figure A2.18: SWATH Study - Full Load Displacement/Speed - 40t Payload

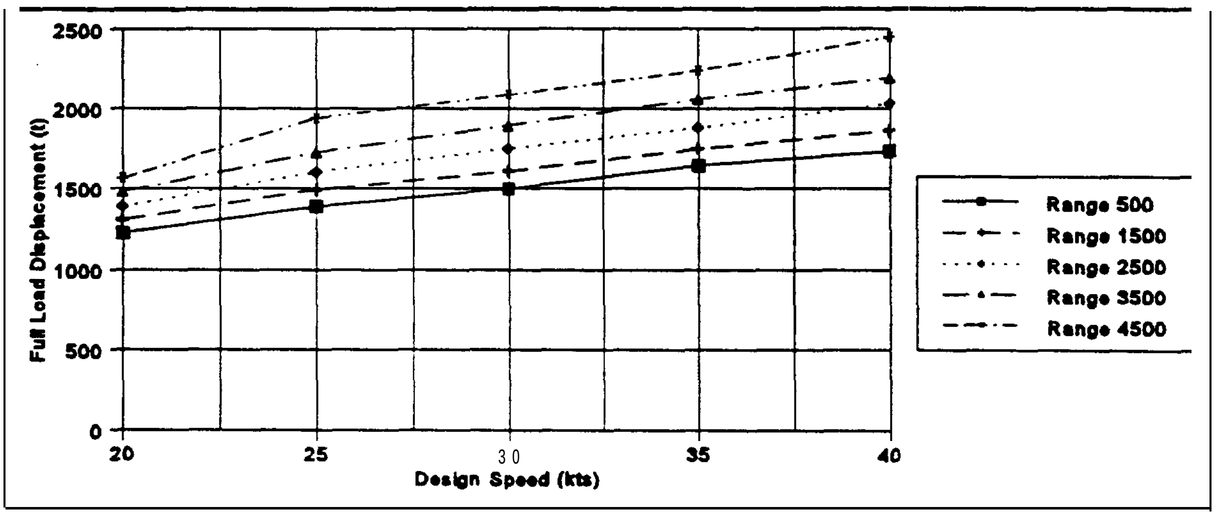


Figure A2.19: **SWATH** Study - Full Load **Displacement/Speed** - **75t** Payload

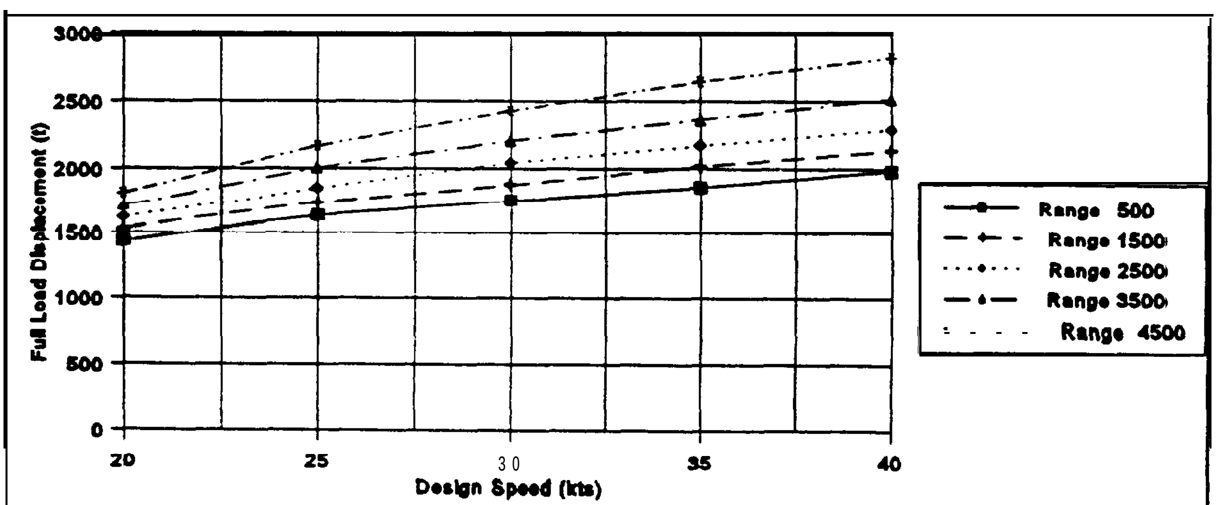


Figure A2.20: SWATH Study - Full Load Displacement/Speed - **90t** Payload

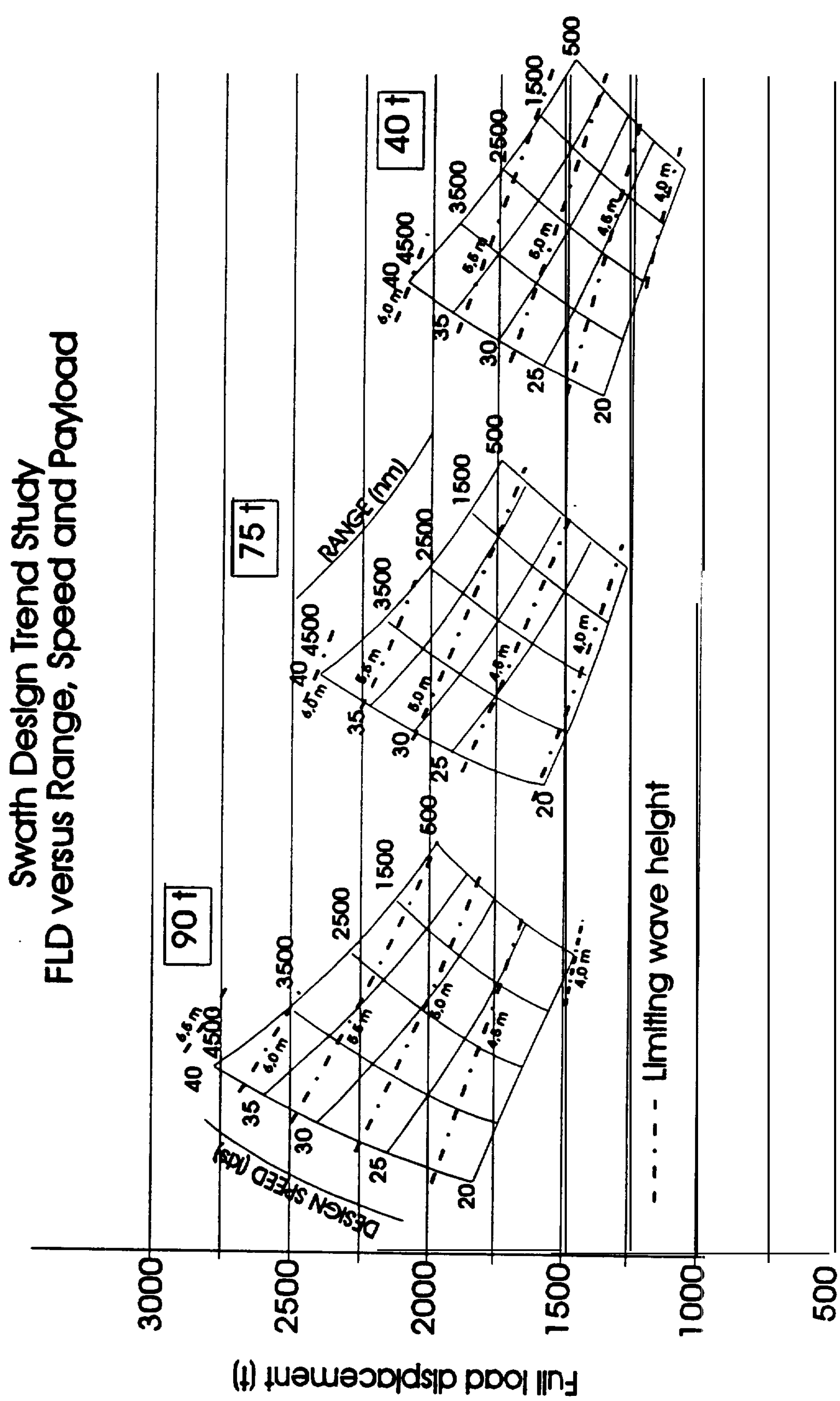


Figure A2.21: SWATH Design Study Results - Full bad Displacement

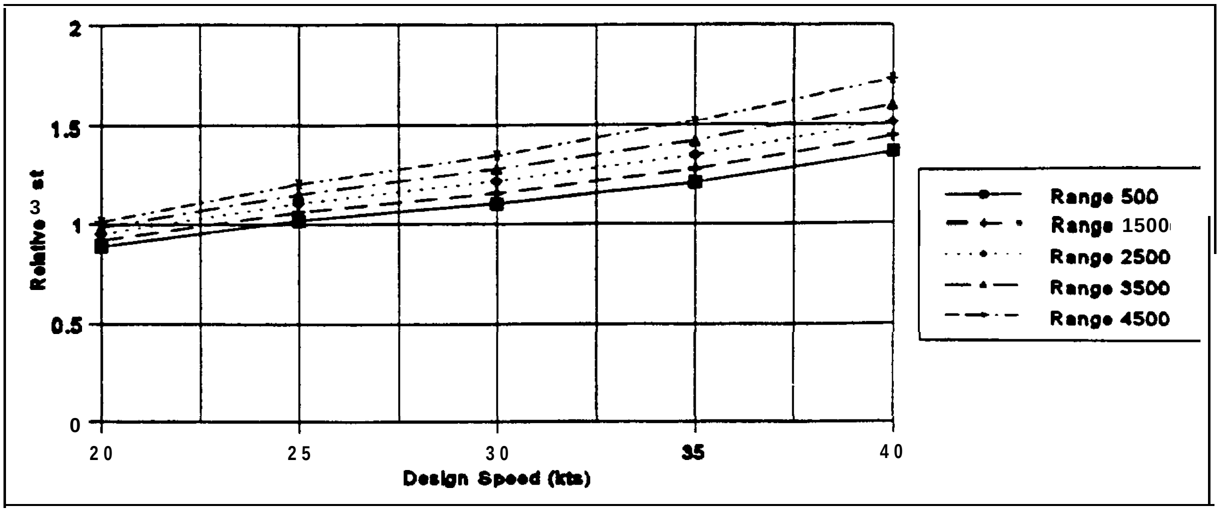


Figure A2.22: SWATH Study - Relative Cost/Speed - 40t Payload

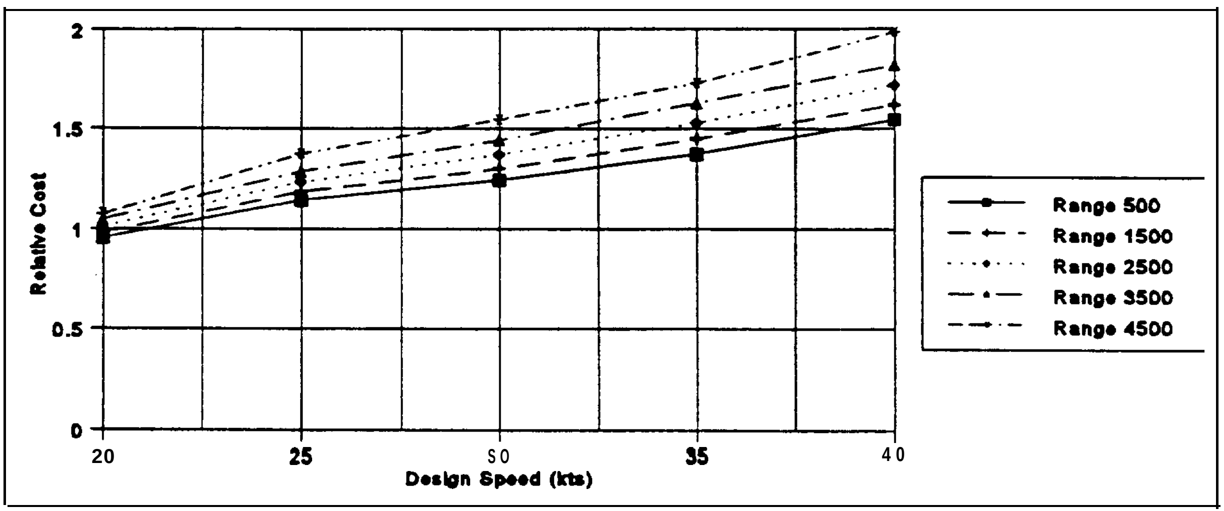


Figure A2.23: SWATH Study - Relative Cost/Speed - 7St Payload

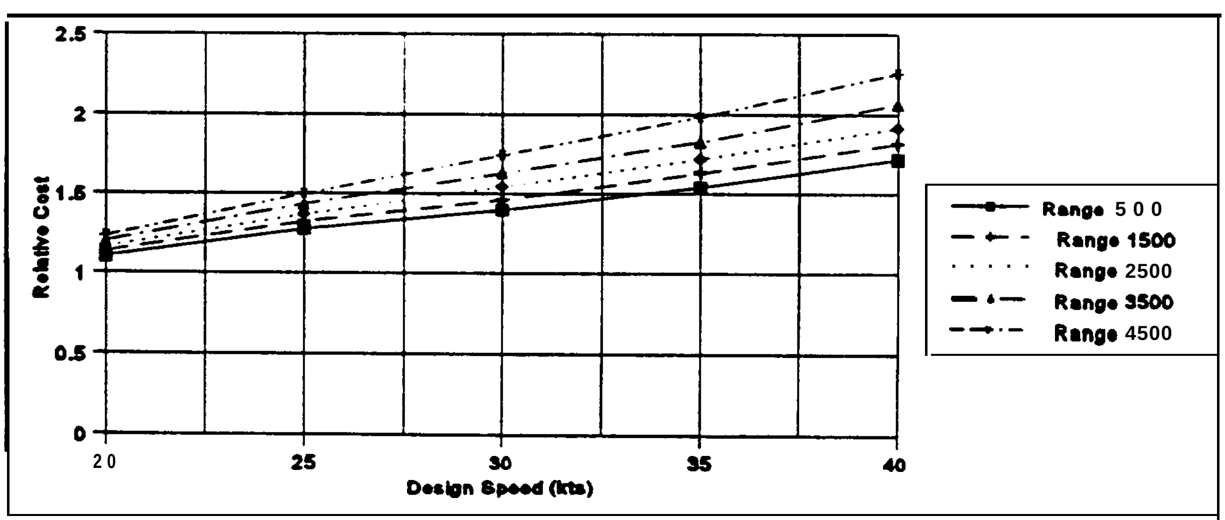


Figure A2.24: SWATH Study - Relative Cost/Speed - 90t Payload

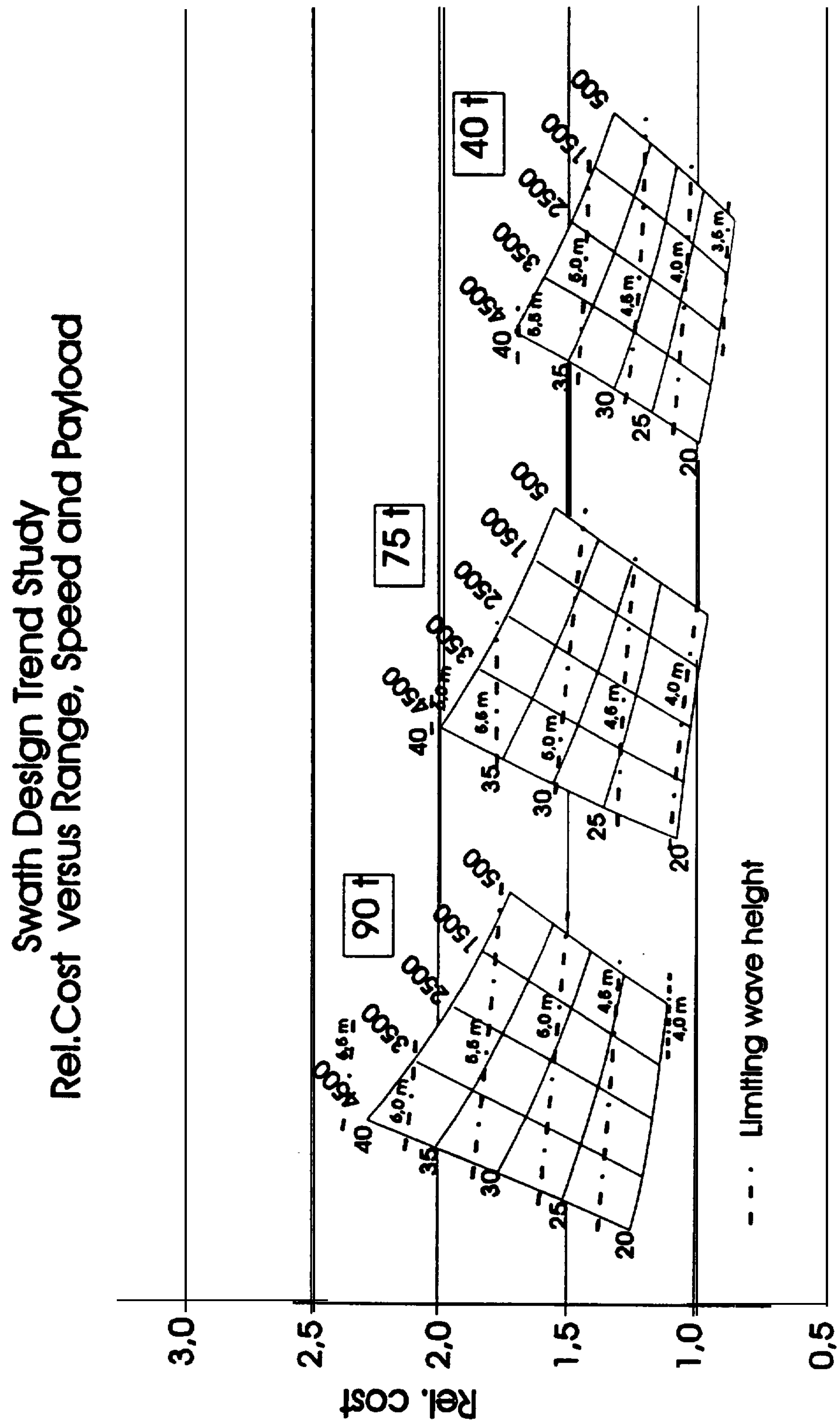


Figure N.25: SWATH Design Study Results - Relative Cost

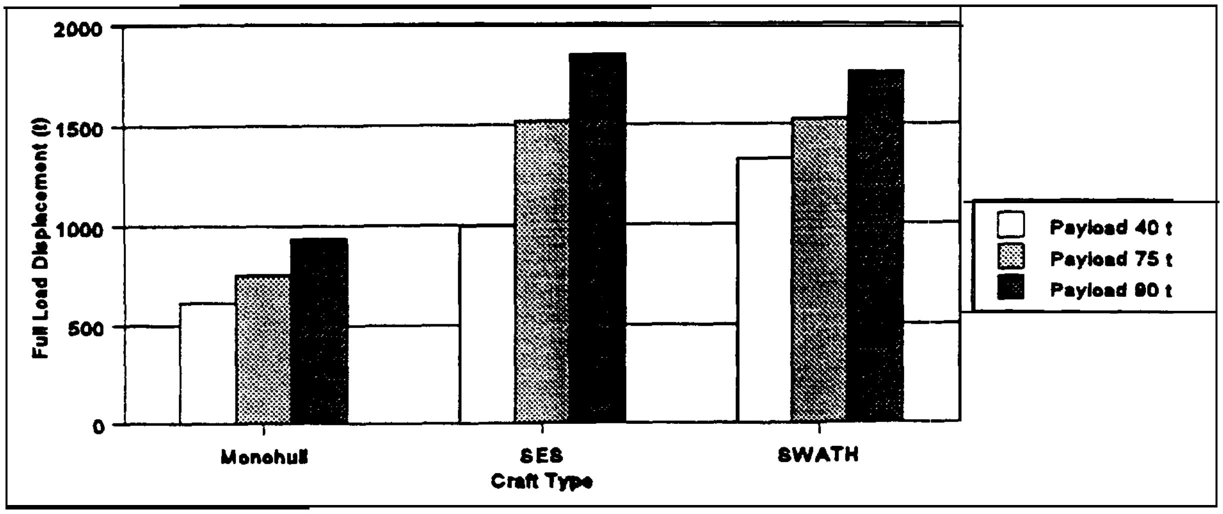


Figure A2.26: Full Load Displacement for Design Speed 20 kts and Range 4000 nm

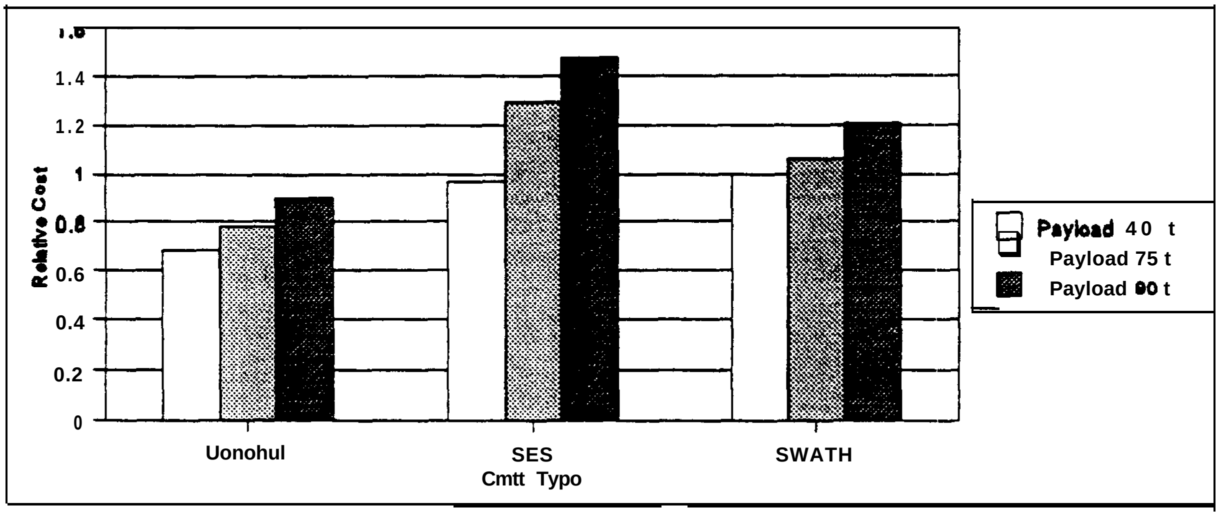


Figure A2.27: Relative Cost for Design Speed 20 kts and Range 4000 nm

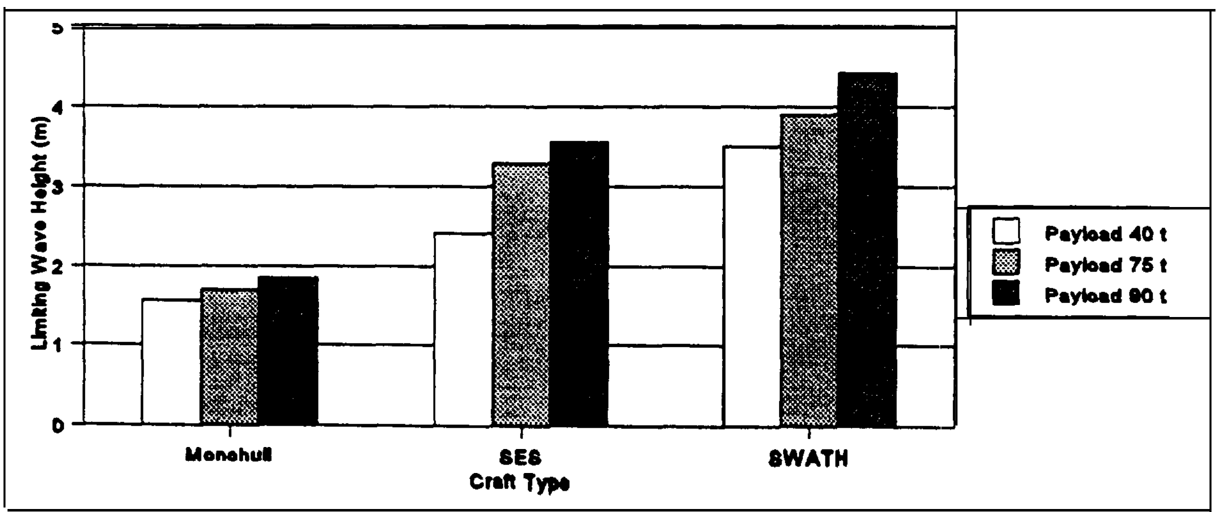


Figure A2.28: Limiting Wave Height for Design Speed 20 kts and Range 4000 nm

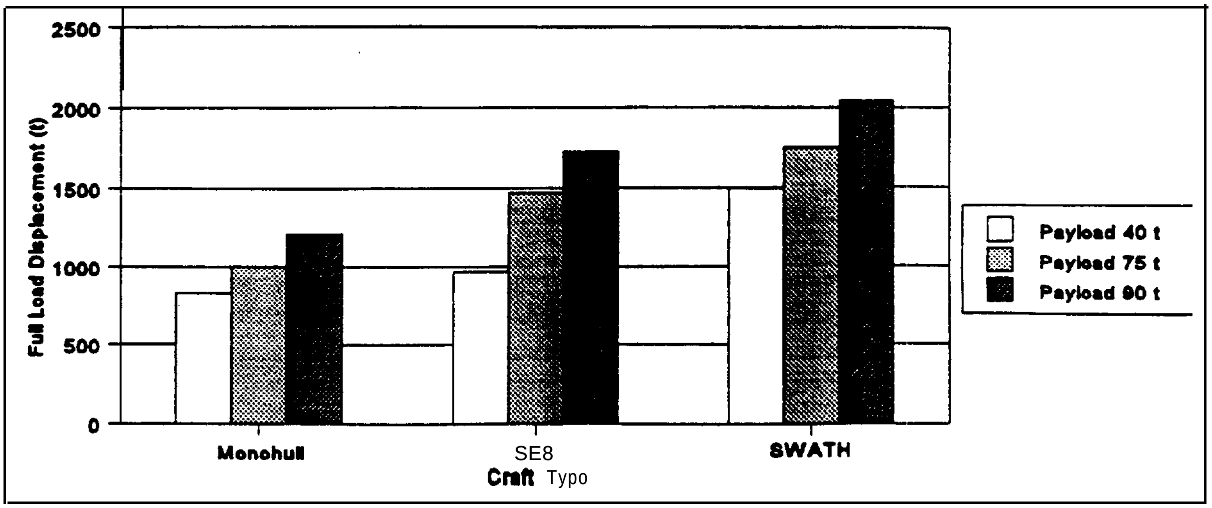


Figure A2.29: Full Load Displacement for Design Speed 30 kts and Range 2500 nm

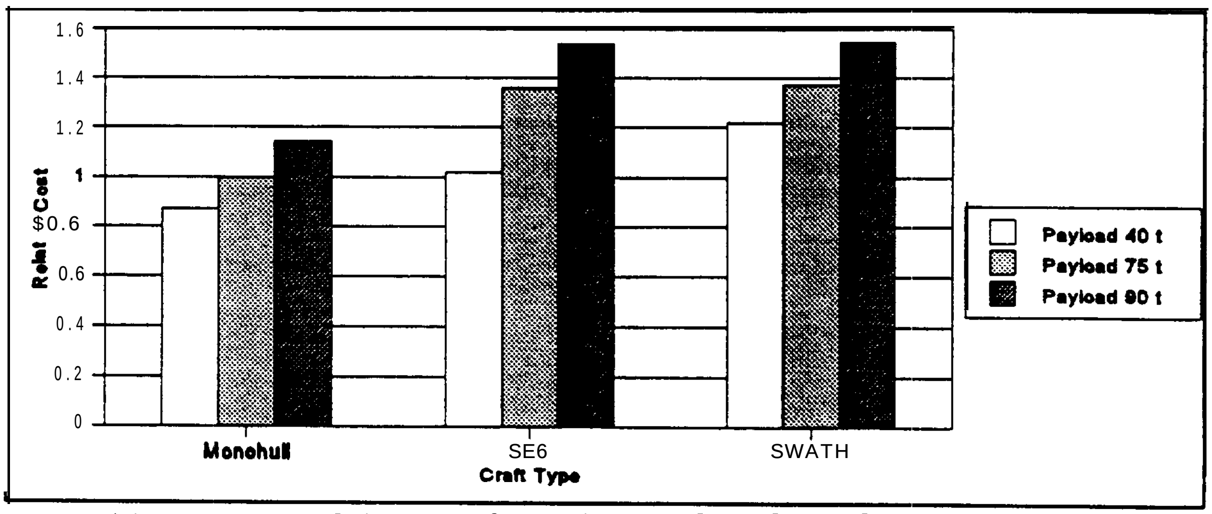


Figure A2.30: Relative Cost for Design Speed 30 kts and Range 2500 nm

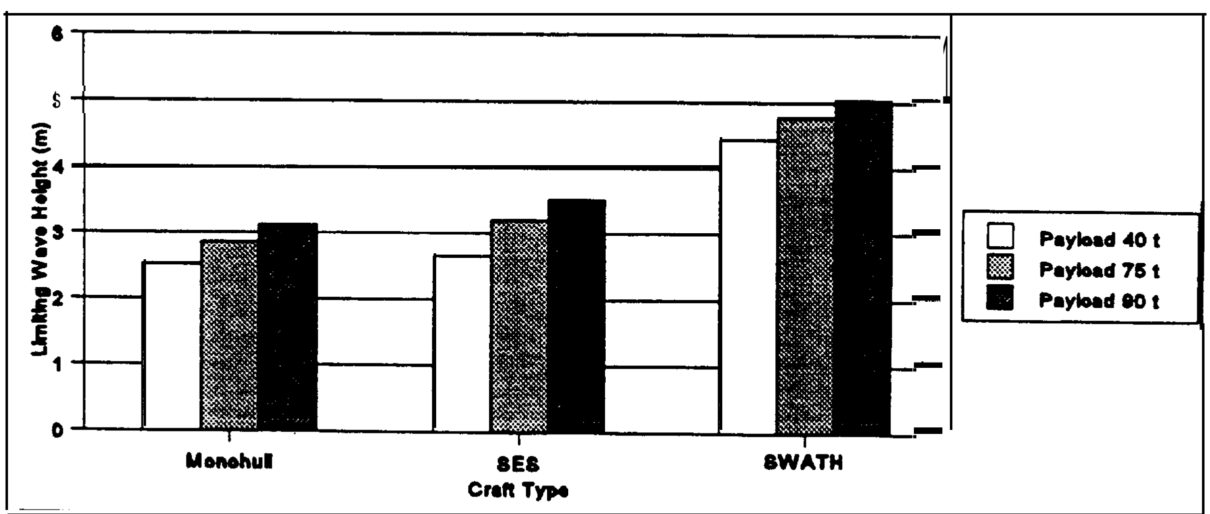


Figure A2.31: Limiting Wave Height for Design Speed 30 kts and Range 2500 nm

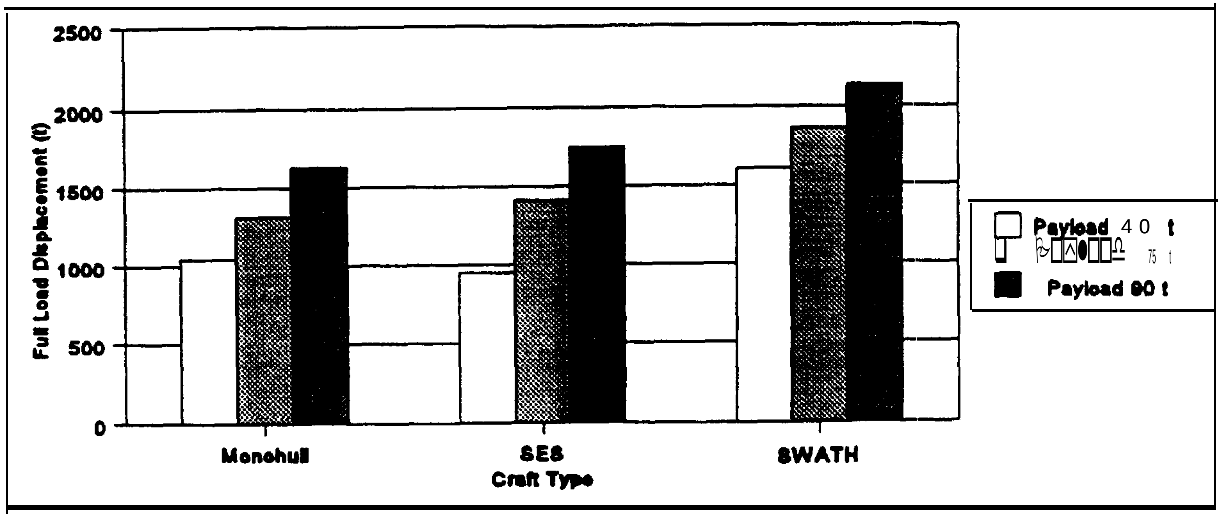


Figure A2.32: Full Load Displacement for Design Speed 40 kts and Range 1500 nm

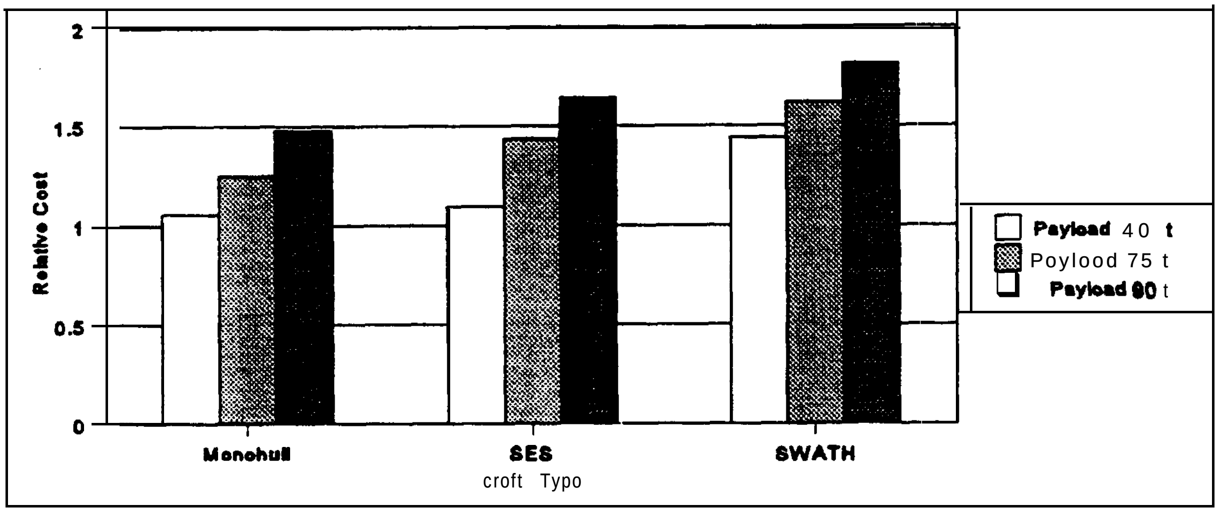


Figure A2.33: Relative Cost for Design Speed 40 kts and Range 1500 nm

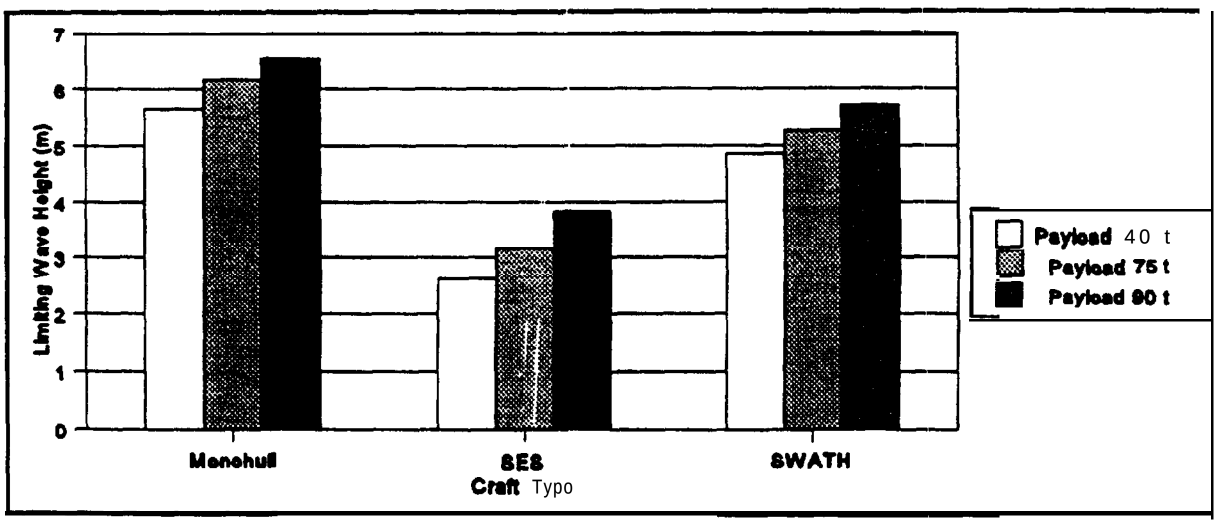


Figure A2.34: Limiting Wave Height for Design Speed 40 kts and Range 1500 nm

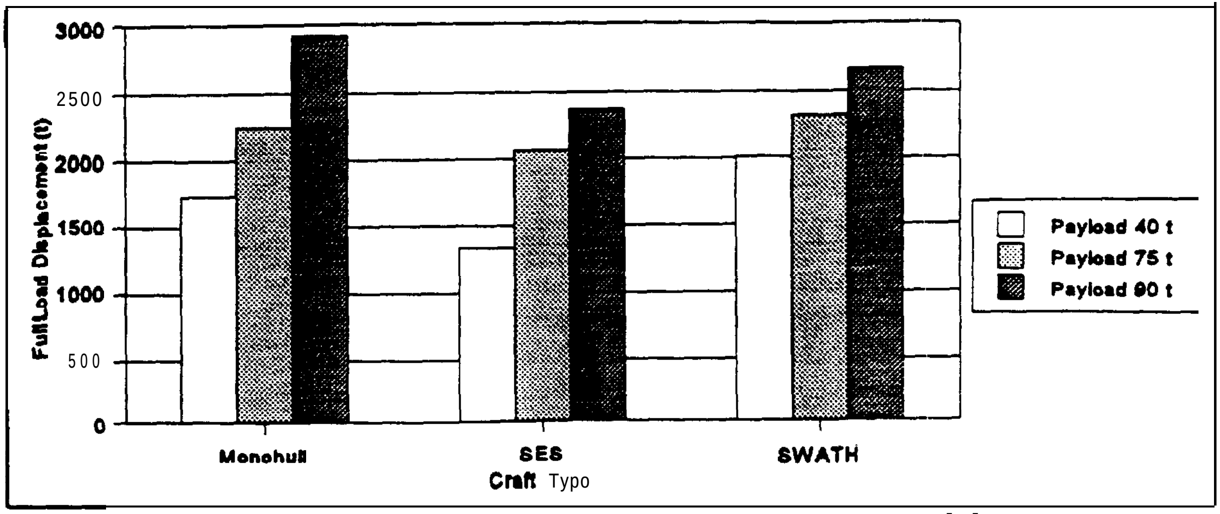


Figure A2.35: Full Load Displacement for Design Speed 40 kts and Range 4000 nm

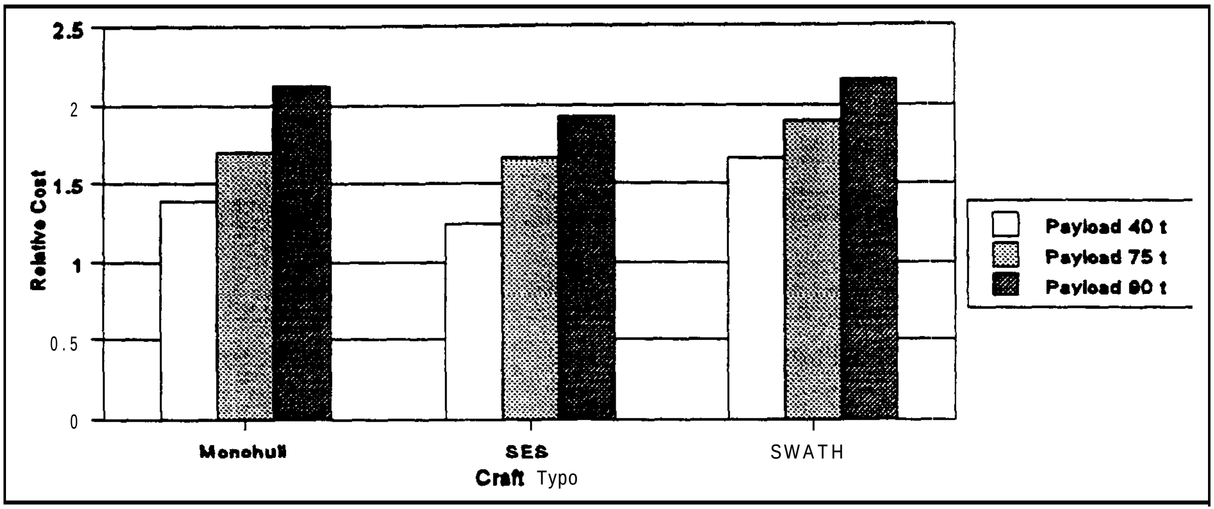


Figure A2.36: Relative Cost for Design Speed 40 kts and Range 4000 nm

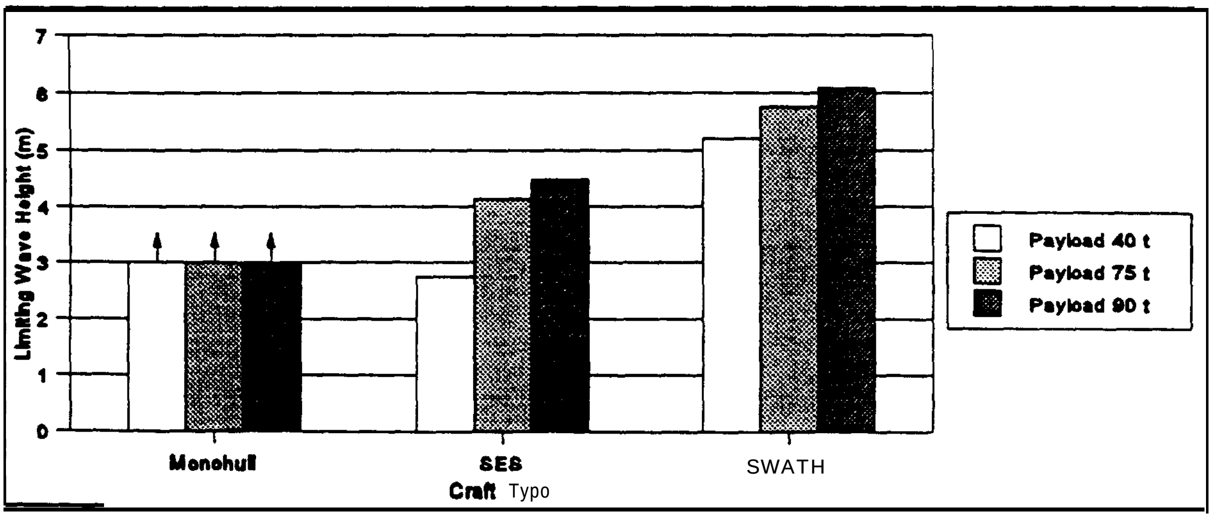


Figure AZ.37: Limiting Wave Height lor Design Speed 40 kts and Range 4000 nm

ANNEX 3.0 - ANALYSIS METHODS

The methods presented in this annex can be used to support a comprehensive requirements analysis design and assessment process leading to the production of a cost-effective solution.

The contributions of the various methods to the overall process is illustrated in figure A3.1.

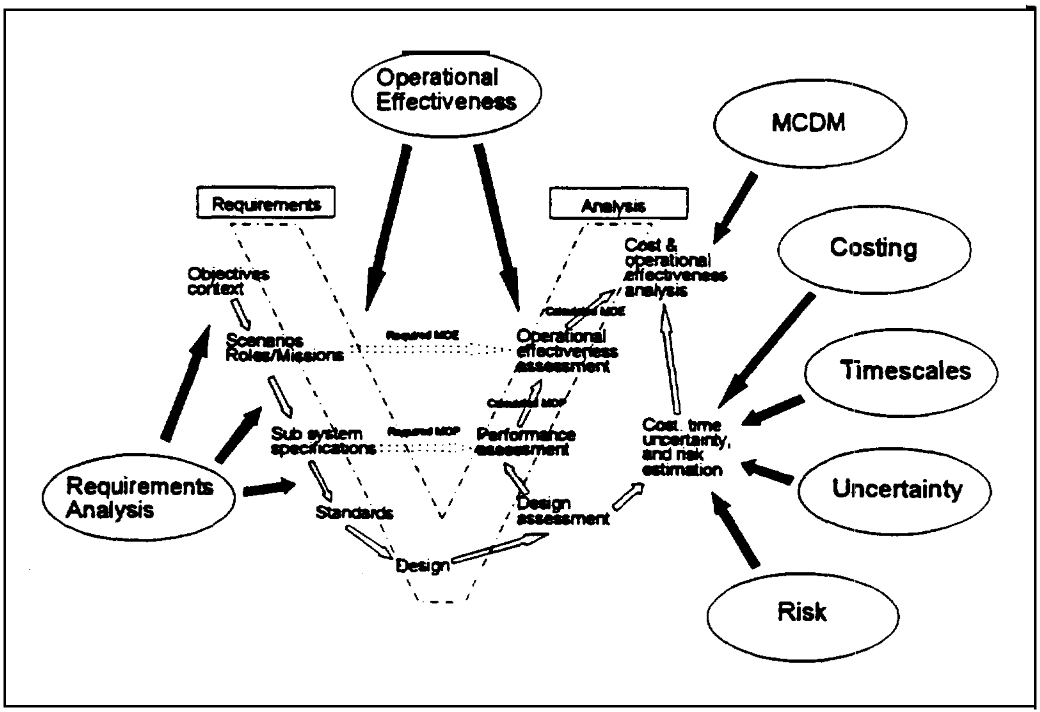


Figure A3.1
Analysis Methods

The techniques can be used at various levels from identifying project elements down to sub-system specification.

A3.1 REQUIREMENTS ANALYSIS

A3.1.1 Introduction

Tbe need to ensure that numbers of requirements are captured and designs then implemented to satisfy them has led to the development of various analysis techniques. Structured analysis is a generic name for format methods designed to manage tbe system development process from requirements capture through to design definition. Requirement development itself is a continuous process that starts with an analysis of the existing situation and proceeds through exploration of possible options towards specification of the preferred solution. Many of the analysis techniques that can potentially be applied to this process and its management have their origins in the field of computer software development and are therefore particularly concerned with processes and data flows. This has led to tbe development of methods having different fundamental perspectives

- **Data Centred**
  The data is considered paramount and processes are established in order to deliver the data to where it is needed. Essentially this perspective is concerned with what constitutes the system.

- **Process Centred**
  These methods treat data as the raw material to be processed and are more concerned with the functions or processes carried out by the system. They deal with how the system operates.

- **Organisation Centred**
  This approach investigates the hierarchies of control and responsibility within the system. It deals with how the system is organised.

These distinctions have become less important as methods have developed, become more integrated and taken a whole system approach. They are now often more related to the system development stages and how the information gathered from one stage flows into, and is then used in, the next. A modern method will be designed to cover

- **Requirements Capture**
  The process of identifying a new system requirement initially involves an analysis of the wider scenario or context within which that system will operate. There is thus a role for simulation and modelling tools and methods in the establishment of requirements. Possible operational modelling methods are described in a later section.

- **Functional analysis**
  Tbe requirements identified are arranged in a logical manner in order to ensure that nothing has been forgotten and no duplication has occurred.

- **Physical partitioning**
  Physical decomposition is an engineering process that relies on an understanding of what is technically feasible in order to effectively design a high level system that carries out the functions and tasks identified. A boundary will be drawn around a particular group of functions that will then be implemented in one sub-system.

- **Sub-system specification**
  A clear statement of the requirements for each element of the overall system will be extracted.

Distinctions between various methods in common use are concerned with differences in emphasis and perspective, varying notation standards and the treatment of timedependent functions and events.

These approaches are extensively used in the development of combat systems which have a heavy dependence on computer hardware and software. Tbe disciplines and techniques involved are however also relevant to non-computer design applications, and some of the methods can be applied directly to general systems analysis. It is during the very early phases of requirements capture, functional analysis and physical partitioning that the methods are most relevant to high level platform concept development. Some techniques are more adaptable and suitable than others for this purpose.

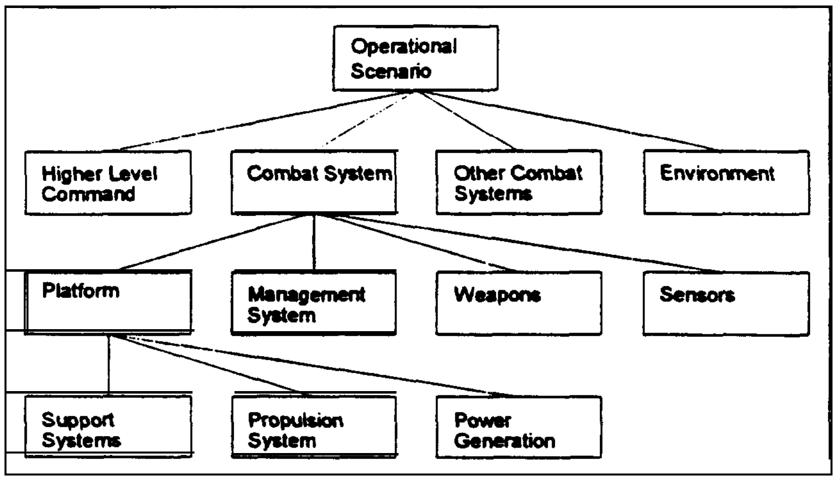
A3.1.2 Analysis Methods

A3.1.2.1 CORE

Method Name	**CORE (Controlled Requirements Expression)**
When to Use	**During the requirements gathering and definition phases**

Method Summary	CORE was developed within a software company, Systems Designers Ltd, to provide a rigorously defined method of specifying requirements. Such a method was needed because inadequate requirement specification is the cause of many system development projects failure to meet cost and performance targets. Although developed in the software environment it is applicable to more general system specification tasks.
	
	The method is divided into two main stages as follows
	
	- **startup**
	This is the problem definition phase and seeks to define the objectives and needs for the new system. There are two key elements
	  - **Viewpoint structure**
	  This defines the logical and physical components of the environment and the system
	  - **Work statement**
	  This is essentially the project management element of the analysis
	
	- **Data gathering**
	Various kinds of data are collected, divided broadly into
	  - Tables
	  These contain details of data indicating their sources, inputs, actions, outputs and destinations.
	  - **Data Management**
	  This is essentially a data dictionary managing information.
	  - Data Structure Dii
	  Contains information on how data is arranged.
	  - **isolated Viewpoint Action Diagrams**
	  These illustrate data flows and transformations together with time dependencies.

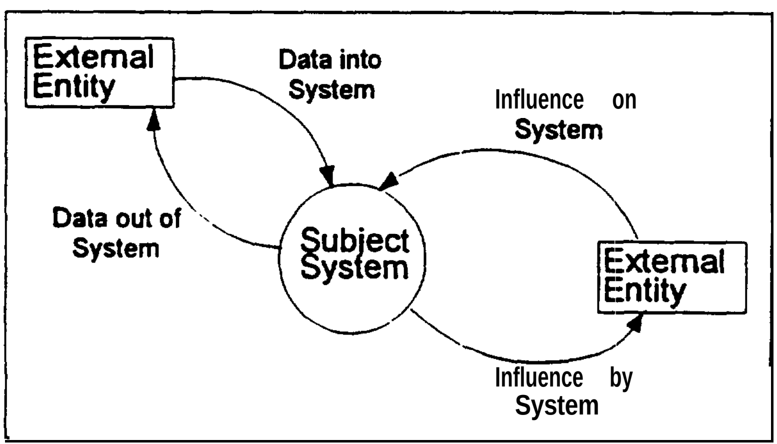
Advantages	- Tabular collection forms easy to use - Provides simple overall picture - Goodframework on which to hang more detailed models - Highlights system interfaces

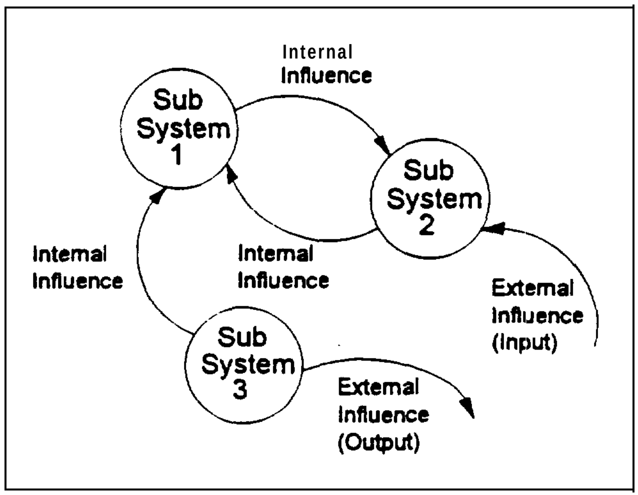
Disadvantages	• Detailed models have no clear picture of behaviour with time • Tends to exclude design issues
Example	In developing the requirements for a mine counter measures vessel there will be a requirement to manoeuvre the ship. However, it is necessary to establish exactly what requirements the ship will have to meet. The first stage is to identify the functions of the combat system. In this respect the platform is itself considered an element of the combat system, and its performance will affect that of the weapons and their handling. More detailed investigation of the dependencies will be required once they are identified, perhaps by modelling. High Level COR 'iewpoint Structures 
References	1, 2

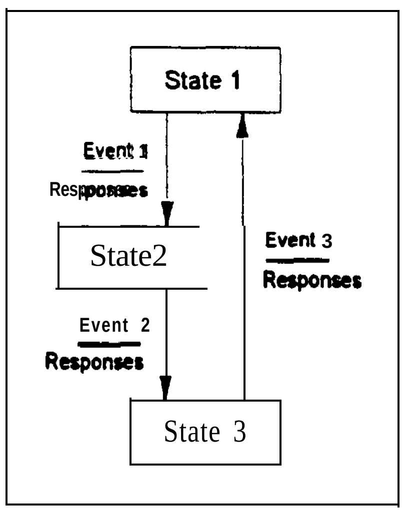
A3.1.2.2 Structured Analysis

Method Name	**Structured Analysis**
When to Use	**During the requirements gathering and definition phases.**
Method Summary	**Structured Analysis is a general term for a formal process of requirements definition. Various proprietary methods have been developed to apply the principles such as Yourdon and IDEF. The approach was developed in** response to the need for better definition of software systems but is applicable to most forms of systems development. Structured Analysis has certain characteristics - Defined process steps and responsibilities - Use of diagrammatic representation - Descriptions of information flows in data dictionary - **Structured language**
Advantages	• Thorough requirements capture • Provision of audit trail • Provides means of communication within project - **Data model can be used to model systems or organisation** - **Same techniques flow from requirements analysis to design and implementation**
Disadvantages	- **Particular implementation method may not deal with** all characteristics **and parts of system.**
Example	**See Sections A3.1.2.3 and A3.1.2.4.**
References	**3, 4, 5**

A3.1.2.3 Yourdon Structured Method

Method Name	Yourdon Structured Method
When to Use	During the requirements gathering and system definition phases.
Method Summary	The Yourdon method concentrates on three perspectives or views of a system and has a modelling tool appropriate to each. In addition there are three techniques to link the three primary viewpoints. The primary views are - **Function** Data flow diagrams are used to show what the system does. - **Time** Event lists are used to show when things happen. - **Information** Entity relationship diagrams are used to show what information is passed around the system. The linking techniques are - **Function - Time** Behaviour state transition diagram or table. - Time - Information Entity state transition diagram or table. - **Function - Information** Data flow diagrams or function entity table. The first step is to define the bounds of the system and its interdependencies with external agencies. This is done by means of a context diagram. The system under investigation is contained within the central circle. External agencies are drawn in boxes around this. Context Diagram 

<table>
<tr>
<td>Method Summary
(continued)</td>
<td>
The next step is to decompose the system into its major sub-systems. These are shown on a level 0 diagram. All singleended flows correspond to influences to or from external entities in the context diagram.
<u>Level 0 Data Flow Diagram</u>


The process can be repeated for each sub-system producing level 1, 2 or more diagrams. State transition diagrams show the states of a system and the events and conditions that cause the states to change.
<u>State Transition Diagram</u>


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<tr>
<td>Advantages</td>
<td>

Good at detailed requirements definition
Data model can be used to model systems or organisation
Same techniques flow from requirements analysis to design and implementation

</td>
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<td>Disadvantages</td>
<td>

Can be confusing
Does not deal explicitly with interface issues

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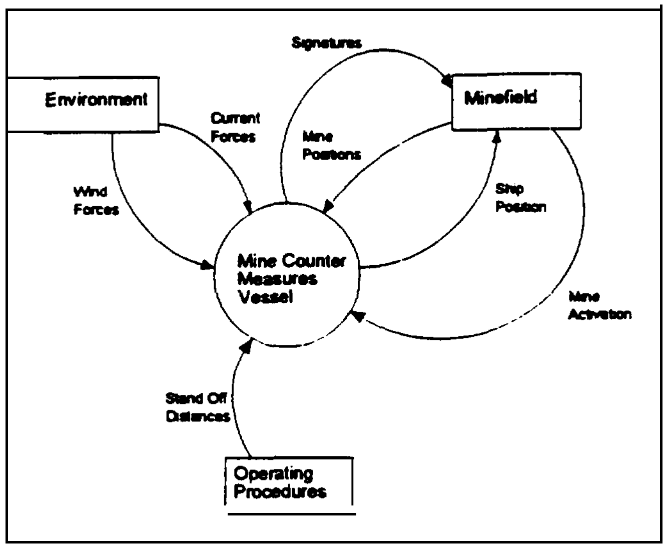
Example

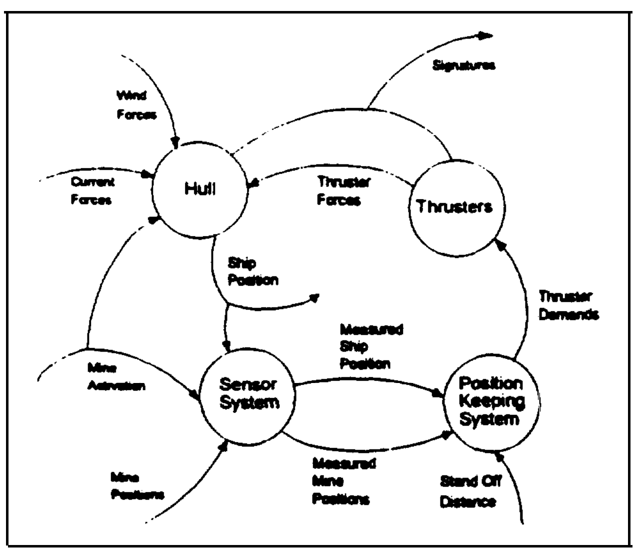
In order to establish a mine counter measure vessel's manoeuvring system parameters it is necessary to establish the ship and its operational scenario. The context diagram for the vessel is defined.

Mine Counter Measures Vessel Context Diagram



The next stage is to define the major components of the mine counter measures vessel. For simplicity only elements directly affecting the manoeuvring function are shown.

Level 0 Mine Counter Measures Vessel

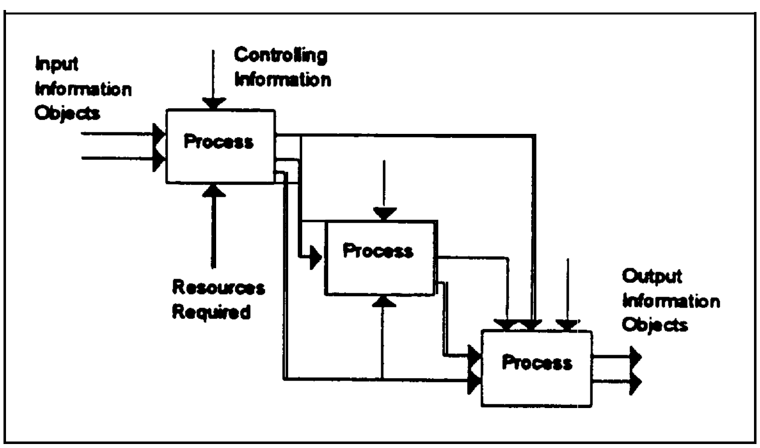


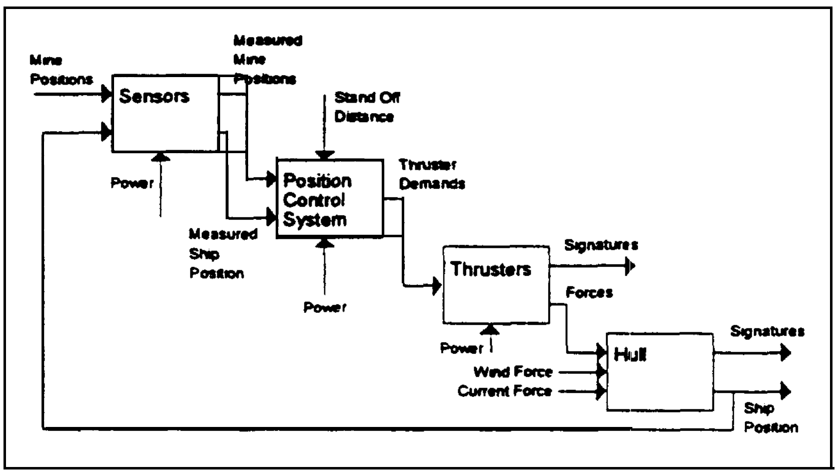
By using this process in more detail all the factors affecting the manoeuvring requirements can be identified. In this case: a general system configuration has been assumed.

References

3, 6

A3.1.2.4 IDEF

Method Name	IDEF (Integrated DEFinition)
When to Use	Process modelling for organisational or technical systems
Method Summary	The IDEF methods were developed to deal with complex systems in which human decision making is a key activity. They have found increasing use for analyzing businesses and organisations. IDEF0 is the diagramming element of the Structured Analysis Method developed by SofTech Inc. There are several related methods: • **IDEF0** This is essentially a process modelling technique. The method is used to describe a system in a top-down highly structured manner. The model incorporates • **Processes** These are the basic building blocks of the system. • **Information** Each process has information flows in and out connecting them to each other. • Objects These connect processes in the same way as information flows. **Resources** The resources required by a process are shown. They may be objects already output from another process. • **Control** Process control structures are shown. Again these may have been produced by another process previously . IDEF0 Model Structure 

Method Summary (continued)	• IDEF 1X This is the complementary modelling technique to the above and uses an entity relationship technique to model the information needed to carry out the processes.
Advantages	• Can be linked to simulation tools in order to model system • General purpose techniques • One model contains a full description of the system
Disadvantages	• Time dependency of information and object flows not considered directly
Example	The major components of a mine counter measures vessel manoeuvring system are shown in the model together with the information and objects. In this example forces are treated as IDEF objects. Mine Counter Measures Vessel Manoeuvring System 
References	7

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A3.2 OPERATIONAL EFFECTIVENESS

A3.2.1 Introduction

Once a new system is used operationally its effect on the strategic or tactical situation may be determined. However it is necessary to predict this likely benefit in as simple a way as possible at the early design stages. This is achieved by defining a measure or measures of effectiveness at the overall operational level within which the proposed system will operate.

The purpose of operational effectiveness analysis is to generate metrics that allow the direct comparison of alternative systems that may have totally different physical characteristics and measures of performance. Methods must therefore take as input sub-system and system measures of performance, information on tbe surrounding environment and data describing interacting systems and use this to calculate measures of effectiveness.

A3.2.2 Measures of Performance

Measures of performance describe directly measurable functional characteristics of a sub-system or system under defined conditions. They may be defined at sub-system or system level as follows

- Propulsion machinery
  - Revolutions and power curves
  - Fuel consumption curves
  - Mean time between failure
- Hull
  - Speed power curves
  - Seakeeping/operability
  - Shock limits
- Weapon system
  - Probability of detection
  - Circular error probability
  - Slew rate

Whole Warship
- Mobility
- Mission support
- Readiness
- Survivability
- communications
- Command and control
- Human support

These figures are output from

- Design assessment and analysis procedures
  Predictions are generally made either by analogy with past designs or by analytic prediction methods.
- Model or prototype testing
  As the design develops model tests will he made, particularly in order to investigate alternative hull types and forms. Sub-systems may be prototyped and trialled and their performance measured.

A3.2.3 Measures of Effectiveness

Measures of effectiveness describe tbe effects a military system is able to produce on a military situation in a defined scenario and environment. It is preferable to limit their number and to define them at as high a level as possible. Generally they will be defined in terms of the strategic scenario within which the proposed system is operating (reference 1). Secondary figures may sometimes be necessary in order to bring out important differentiators between systems. Examples for particular warship types and their weapon systems could include

- **Patrol Vessel**
  - Primary: Amount of contraband recovered
- **Mine Counter Measures Vessel**
  - Primary: Risk to subsequent shipping crossing the area
  - Secondary: Clearance rate for given risk to subsequent shipping
- **Air Defence Frigate**
  - Primary: Task group losses

These values are output from operational effectiveness analyses.

Measures of performance can thus become the input data for operational effectiveness prediction methods that generate measures of effectiveness. For example a simulation model of the operation of a mine counter measures vessel will take as input such MOPs as

- **Platform**
  - Speeds
  - Signatures
  - Manoeuvrability
- **Payload**
  - Sensor sensitivities and ranges
  - Weapon kill probabilities
- **Mine**
  - Sensitivities
  - Danger radii

and will output high level MOEs such as

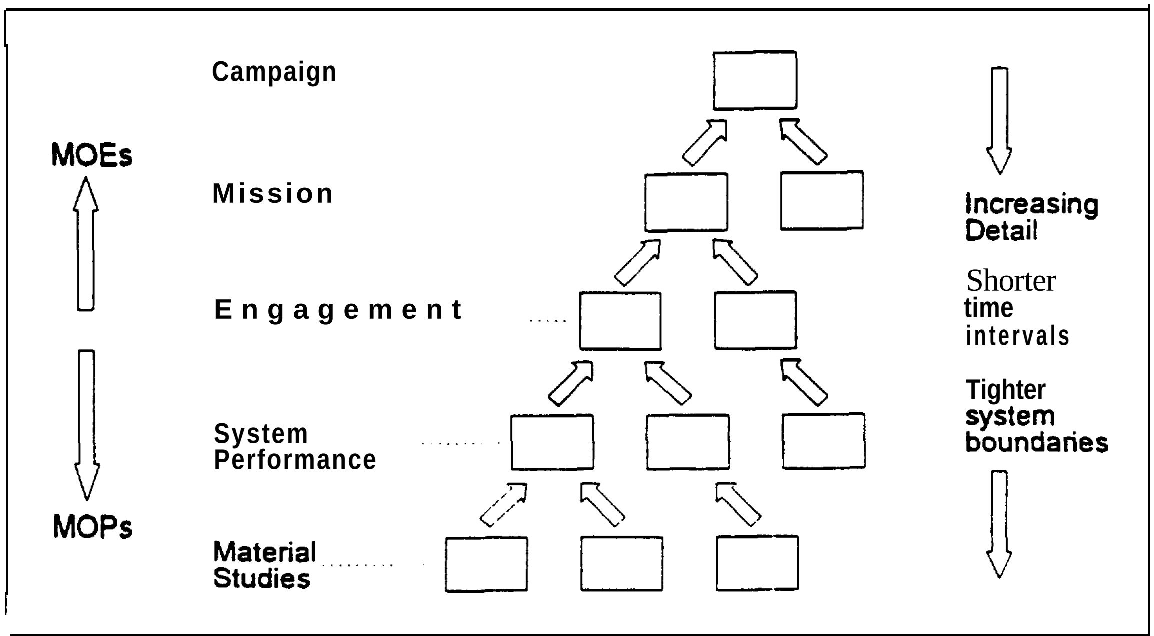
- **Risk to subsequent shipping**
- **Clearance rate for given risk to subsequent shipping**

It is conceivable that a measure of effectiveness for one system could become a measure of performance when considering the effectiveness of a larger higher level system.

The techniques described in later sections can be used to derive both MOPs and MOEs. The distinction really depends upon the boundaries of the system under consideration in relation to the particular elements being analysed. If a sub system is being considered then this will result in an MOP which can contribute to the calculation of an MOE for the larger system.

A hierarchy of analyses can thus be performed ranging from low level material studies involving a great amount of detail to high level campaign models. Each layer in the hierarchy uses results from the levels below it.

Hierarchy of Analysis



A3.2.4 **Preliminary Options**

Before complex modelling and simulation are used there are some **non** mathematical techniques that can be used to obtain MOPs or MOEs.

A3.2.4.1 **"Real" Ship vs. Model of Ship**

This option should always he considered at the first stage of analysis to determine whether making the approximations inherent in any modelling process is absolutely **necessary. Options** for the use of models of the system are given in section A3.2.4.2.

Method Name	Investigate using "Real" Ship
Method Summary	**This** will, in general, involve either building a full scale prototype of the system to be **analysed,** or modifying an existing system to perform in a manner equivalent to the subject.
Advantages	Eliminates any errors or approximations introduced by models or **simulations.**
Disadvantages	• Usually prohibitively expensive
Example	• **An in service ship may be modified to act as a trial vessel for a new system. Generally this will be a payload or weapon system although alternative propulsion systems may also be trialled.**
References	4

A3.2.4.2 **Physical Scale Model vs. Mathematical Model**

In general, it is more beneficial to use a model of the system than go to the time and expense of building a full scale prototype, even though this will inevitably introduce errors into the investigation. The justification for doing this is that models are generally orders of magnitude cheaper than building a full scale version.

Having established that a model is required, there is the option of using either a physical scale model or using a mathematical model. Details of using mathematical models are given in the section A3.2.5.

Method Name	**Use a Physical Scale Model**
Method Summary	It is sometimes useful to build a physical model of the system to be studied. Indeed, where there is no theoretical precedent to an offered design, it is vital to build a physical model to establish any "unknowns" which may not be covered by traditional theory. Scale model tests can be used to obtain measures of performance such as speed and sea-keeping data, but are of little use in deriving measures of effectiveness. These can only be obtained from operational exercises or mathematical simulations.
Advantages	- **Ensures that any "unknowns" in accepted theory are taken into consideration.**
Disadvantages	- **Can be a time consuming, inflexible and expensive method to use, especially if there are a variety of systems to be studied.**
Example	**Tank testing of scale models has long been used to obtain platform measures of performance.**
References	**4**

A3.2.5 Mathematical Modelling Methods

Mathematical modelling techniques are the most effective tools available to the operational analyst, particularly when used in conjunction with the powerful computers readily available today. They are reliable, in that all results are reproducible and implementation of accepted theory is not subject to calculation or implementation errors. They are flexible, in that there are many general purpose modelling programs available, and any model specific to one scenario should be easily modified to deal with small system design changes. Mathematical models are efficient because it is possible to model a relatively complicated system and scenario in a matter of days, and to produce results for variations of system and scenario in minutes.

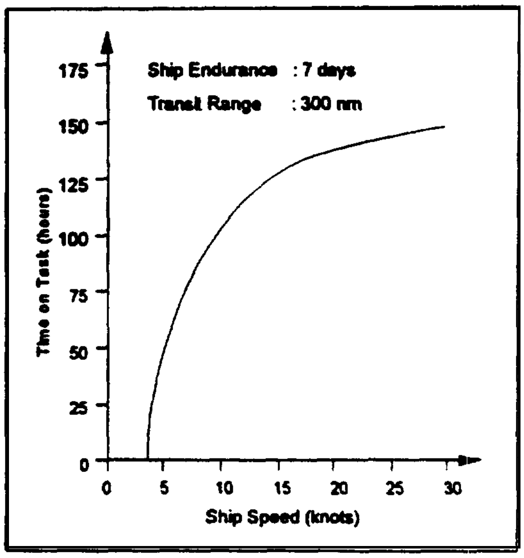
There are various mathematical modelling techniques available, each with their advantages and disadvantages, depending on the system and scenario to be modelled. The most direct method is to seek an analytical solution to the problem. If one is available and is computationally efficient, it is usually desirable to study the model in this way rather than through other simulation methods. However, many systems are highly complex, particularly where parameters can only be described in statistical terms. This means that valid mathematical models of them are also complex, precluding any possibility of an analytical solution.

Of the remaining techniques available, discrete-event simulations are perhaps tlhe most versatile. They work by reducing a complicated procedure or “mission” into a series of inter-related events. Other simulation methods, such as queuing and continuous simulations are often of more use in more specific situations. All of these methods are addressed in the following sections.

An acknowledged problem with mathematical modelling of operational effectiveness is the difficulty of incorporating the effects of human decision making and tactics. These deficiencies are being addressed by the incorporation of rule based systems and decision modelling methods akin to those described in later sections.

A3.2.5.1 **Analytical Solution**

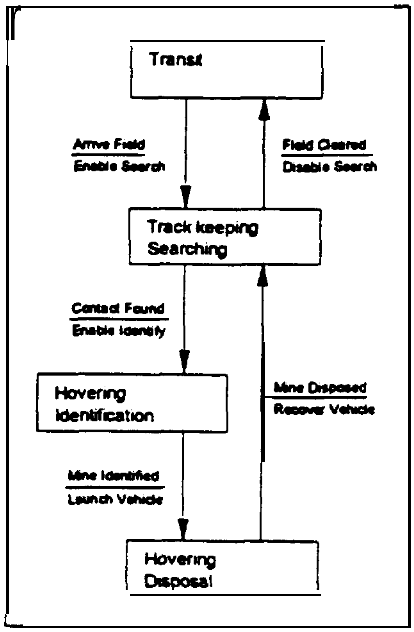
Method Name	**Analytical** Solution
Method Summary	**Analytic solutions** are used when the mathematics of a model are simple enough to be (a) written down in a complete and coherent **manner,** and **(b)** solved. Such a solution is "exact" in the mathematical **sense** but its applicability to the real world will depend heavily on the complexity and detail of the equations and data used to feed **the** equations. Perhaps the simplest of analytic solutions is the relation **d = s x t** where d = Distance travelled **s** = Rate of travel t = Time spent **travelling** It will be noted that whilst this may be a valid model for an **idealised** or simple case ***(eg.*** ship cruising at constant speed for 12 hours in calm weather), to accurately model a real situation in detail, perturbations to the ship's movements will need to be taken into account (wind, tide, sea state, speed variations erc.) In this way, analytical solutions can rapidly become highly complex. For more complex models, keeping track of the **equations** on paper, let alone solving them, can quickly become impractical. Spreadsheet programs are a particularly useful alternative to pen and paper when developing complex analytical models. Modern spreadsheet programs provide the analyst with a host of tools to determine the performance of a system. For example, spreadsheets will automatically perform regression and statistical analysis on data sets, allow the analyst to manipulate the data using data sort functions and display the data in a range of graphical and tabular formats.
Advantages	• Ensures the results are "exact" to a level commensurate with the accuracy of the model.
Disadvantages	- To determine the analytical solution to even a moderately complex system can he an extremely time consuming and difficult process. Having achieved a solution, it is then necessary to determine a method to solve it, which may be an equally arduous task.
Example	**A** ship with an endurance of 7 days is required to perform operations in an area 300 miles from its home port. Describe the effect that transit speed has on the time-on-task of the ship. Input Data d = Endurance (days) R = Transit Range (nautical miles) **s** = speed (lam) Calculated Data **t** = Transit time one way (hours) **d' = 24 x d (hours)** . t = **R / s (hours)**

Example (continued)	Time on Task = d' • (2 x t) Time on Task = 24 x d - (2 x R / s) Fixingd = 7andR = 300 gives 
References	4, 5, 6

A 3 . 2 . 5 . 2 Discrete-Event Simulation

Method Name	Discrete-Event Simulation
Method Summary	Discrete-event simulations model a system as it evolves over time. They are performed by representing the system with a set of state variables which change instantaneously at separate points in time. These points in time are when an event occurs, where an event is defined as an instantaneous occurrence that may change the state of the system. Although discrete-event simulations could be conceptually performed by hand calculations, the amount of data that must be stored and manipulated for most real-world systems dictates that discrete-event simulations be performed on a computer. Because of the dynamic nature of the simulation process, it is necessary to monitor the passage of time from event to event. This is performed by what is known as the simulation clock which quite simply gives the current value of the simulated time. There are two principal methods of advancing the simulation clock. These are known as nextcvent time advance and fixed-increment time advance. The first approach is by far the most common method to be used by simulation languages. It works as follows: 1. Set the system state variables to the initial conditions and reset statistical output variables 2. Set the simulation clock to zero 3. Get a list of possible *events* from the current system state 4. Determine the times when the possible events could occur (if at all) 5. Select the earliest of those events 6. Update the system state to reflect the effects of the event 7. Update statistical variables 8. Update the simulation clock to the time that the event occurred 9. Return to step 3. This loop is repeated until a predefined system state or clock time is reached, whereupon the results of the simulation are displayed (usually the values of the statistical variables). Using this method of time increment means that long periods of inactivity are skipped over by the simulation clock. It should also be noted that the successive jumps of the simulation clock are generally variable (or unequal) in size.

Method Summary (continued)	With the fixed-increment time advance method, the simulation clock is advanced in increments of exactly At time units, for some appropriate choice of At. After each update of the clock, a **check** is made to determine if any events should have occurred during the previous interval of length At. If this is the case then they are assumed to have occurred at the end of the At period and the system state variables are updated at that time. **This** means that two events which occur at slightly different times may be assumed to occur at the same time if the interval between them is less than At. The possibility of such an error arising may be reduced by making At smaller, but increasing the event-checking rate can put a significant overhead on the amount of computing required and **hence** slow down the simulation process.
Advantages	- The flexibility of the **discrete-event** model means that it can be applied to a variety of systems and scenarios. The events themselves can take on various forms; normal sequential events guide the passage time and follow the natural course of a mission; decision events allow the model to alter the course of the mission according to the current circumstances; and random events, such as equipment failures, occur spontaneously (randomly) and cannot be predicted. Combinations of these various events can lead to very detailed and useful modelling tools. • Another advantage with using event simulations is that by breaking a mission into a logical set of events, the actual analysis and use of the model is intuitive in the sense that the ship can be “seen” performing the mission by monitoring the flow of events.
Disadvantages	• Event simulation models are generally created by writing a computer program to perform the simulation. Not only does this mean that a detailed knowledge of a programming language is required, but that making changes to the model may involve some element of re-programming. • Depending on the complexity of the model, and the nature of the mission being simulated, it can be a time consuming process to perform analysis using this method when compared to analytical solutions.
Example	Discrete Event simulations are of great value in **modelling** operational missions where a naval vehicle interacts with other craft or systems. Examples include patrol and search mission, the passage of a mine counter measures vessel through a minefield or an anti-submarine engagement, **The** discrete event simulation can be described by the state **transition** diagrams of a formal systems analysis methodology. These are described **in** section **A3.1** and an example for a simplified mine clearance operation is **shown.**

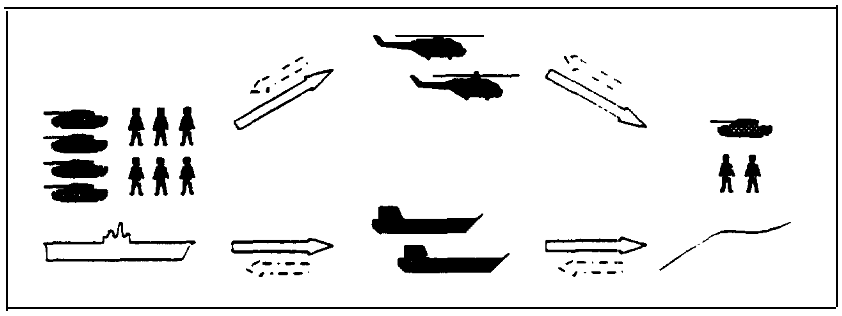
Example (continued)	**States and Events for Mine Clearance** 
References	3.4

A3.2.5.3 Queuing Simulation

<table>
<tr><th>Method Name</th><th>Queuing Simulation</th></tr>
<tr><td>Method Summary</td><td>Queuing simulations consist of one or more servers that provide service of some kind to arriving customers. This terminology derives from the classic examples of a queuing simulation, such as banks or post offices. Customers arrive and are processed by servers. Customers who arrive to find a server free may go straight to that server and be processed immediately. Customers who arrive to find all servers busy join one or more queues, hence the name “queuing” simulation. In practice, the method can be applied to a whole range of scenarios which share the servers and customers. Examples of such systems are shown below.

<table>
<tr><th>System</th><th>Servers</th><th>Customers</th></tr>
<tr><td>Bank</td><td>Tellers</td><td>Customers</td></tr>
<tr><td>Computer System</td><td>CPU, Peripherals</td><td>Jobs</td></tr>
<tr><td>Airport</td><td>Runways, Gates, Check-ins</td><td>Airplanes, Passengers</td></tr>
<tr><td>Communication System</td><td>Lines, Circuits, Operators</td><td>Calls, Callers</td></tr>
</table>

Queuing simulations are usually performed using discreteevent models although mathematical analysis of more straightforward situations is often possible. There are three results which are usually of interest; first, the expected average delay in the queue experienced by a customer; second, the average number of customers waiting in a queue; and thirdly, how busy the servers are, which is the expected proportion (percentage) of time during the simulation when the server is busy (not idle).</td></tr>
<tr><td>Advantages</td><td>- This method can be extremely useful for the range of scenarios described above. It provides an accurate, intuitive way at arriving at sensible results, and has the added benefit that the model is usually easy to construct.</td></tr>
<tr><td>Disadvantages</td><td>- The method is very limited in the scope. A slight alteration in the problem definition may mean that the method is no longer applicable.</td></tr>
<tr><td>Example</td><td>An example of a marine operation suitable for this modelling technique would be the unloading of equipment and men from an assault ship. Here, the “servers” are the landing craft and helicopters used to disembark the men and equipment (the "customers").</td></tr>
</table>

Example (continued)	Amphibious Landing Simulation 
References	2. 4. 7

A3.2.5.4 Continuous Simulation

Method Name	Continuous Simulation
Method Summary	Continuous Simulation concerns the modelling over time of a system by a representation in which the state variables change continuously with respect to time. Typically, continuous simulation models involve differential equations that give relationships for the rates of change of the state variables with time. If the differential equations are particularly simple, they can be solved analytically to give the values of the state variables for all values of time as a function of the values of the state variables at time zero. For most continuous models, analytic solutions are not possible, however, and numerical analysis techniques such as Runge-Kutta integration must be used to integrate the differential equations, given specific values for the state variables at time zero.
Advantages	- Continuous simulations are similar to analytic solutions in that solutions to both are exact. In practice this means that the level of accuracy achieved from the modelling process is directly related to the level of detail described by the model. There are however generally some inaccuracies arising from the use of numerical integration procedures. - Continuous simulations, however, have time as the driving variable. The equations are structured so that the time variable may be "played" and variables of interest monitored to establish their characteristics.
Disadvantages	- As with analytic solutions, creating the equations to describe even a limited scenario can be a very difficult task. Even when a series of equations has been developed, it is by no means certain that the series of equations can be easily solved. - In general, the technique is limited to simple dynamic situations such as those described in the Examples section.
Example	Such techniques are used to model complex systems that are in continuous change. The dynamic behaviour of a ride control or manoeuvring system can only be determined by using such techniques. Complex weapon engagements are also amenable to continuous simulation models although in most cases numerical solution methods must be used.
References	4, 8

A3.2.5.5 **Monte-Carlo Simulation**

Method Name	**Monte Carlo Simulation**
Method Summary	The term "Monte Carlo Simulation" was coined during World War II when it was applied to many problems associated **with** the development of the **atomic** bomb. Its primary characteristic is tbe use of random variables in determining the outcome of a simulation; hence the name "Monte Carlo". **Although** the name has been applied to any simulation model employing random variables, there is one particular subset to which it is most often applied, **This** is where the system and scenario can be described using a series of equations, similar to the analytical solution **case,** but where either the equations cannot be solved using standard numerical techniques, or where one or more of the input parameters takes the form of a statistical random spread, rather than a specific value, In the former case, where the equations are so complex as to prohibit normal solving techniques (such as in a multi-integral function, with an ill-behaved integrand), it is often possible to use the Monte Carlo method to find a solution to the function. More interestingly is the latter case, where a system and scenario have been well modelled, but one or more of the input variables has a random spread of specific distribution associated with it. For example, equipment failures in Availability, Reliability, Maintainability (ARM) simulations, or the detonation of mines with ship counts during mine-sweeping operations.
Advantages	• The Monte Carlo method provides the operational analyst with a "brute force" method of solving complex models by repeatedly running them until the required parameters have converged. The level of accuracy required is left to the discretion of the analyst.
Disadvantages	• Depending on the nature of the model, the number **of** runs required to converge the parameter of interest may grow very large. This will inevitably lead to a very high computing and monetary over-head. The Monte Carlo method is a "last resort" brute force method if other more direct methods fail. • An additional danger with using the method is psychological. There is a danger in assuming that the more times a model **runs,** and the greater **the** amount of paperwork produced, the more accurate the results will become. This is obviously a fallacy since the level of accuracy produced depends **almost** entirely on the accuracy of the model.
Example	**A** typical use of **Monte Carlo simulation** is in performing Availability, **Reliability &** Maintainability (ARM) studies. **These** are performed by establishing the **interdependence** of one piece of equipment on another, and **one sub-system** on another and grouping these **into a** model of the system as a whole. For each piece of equipment, a **Mean** Time Between Failure **(MTBF)** and a Mean Time **To Repair (MTTR)** are established, along with a **probability** distribution **type** (ea. Normal. exponential) for the failure.

Example (continued)	Additional features may be added to the model, such as number of repair teams, number of spares and whether a piece of equipment can be repaired at sea in a given time (the MTTR), or whether the mission must be aborted and the ship return to port for repairs. Once the model has been created, it can be made to perform a specific mission and complex probabilities solved to determine whether any equipments failed during the mission and if so, how long the ship was inoperable while the equipment was repaired. Performing a single run may reveal that no problems occurred, or that a critical piece of equipment failed 6 hours into the mission and the ship had to return to port. Obviously, reliance on figures from one run is inadvisable, and so the model is run hundreds or thousands of times until reliable performance figures are established.
4, 9rences	

A3.2.6 References

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A3.3 COSTING

A3.3.1 Introduction

Ship costing exercises should consider all elements of the cost of ownership of the proposed design. These elements are fully described in reference 1. The initial cost of designing and procuring a ship are of course only part of the total through life costs. However it is likely that these acquisition costs will be very significant factors in any procurement decision and so much effort has been expended on developing ship cost estimating methods to cover them.

There are basically three levels of cost estimates corresponding to different phases in the procurement process. They can be characterised as follows

	Estimate Type		
	Preliminary	Indicative	Detailed
Procurement Phase	Concept	Feasibility	Project Definition
Technical definition	Low	Medium	High
Work Breakdown Level	High	Medium	Low

Although there are numerous methods and variations available for estimating ship costs. They can be divided simply into two broad categories

- Top-Down Parametric
  These methods are generally used in the earlier procurement phases when the level of technical definition is low and there is a reasonable level of past data that can be used as a basis for estimating the costs of future designs. Their accuracy is limited and the degree of work breakdown is at a high level only.

- Bottom-Up Detailed
  Detailed methods are used for contract estimates. In these methods the high level of technical definition available allows the costs to be estimated at the lowest levels of the work breakdown structure. Individual items are costed, usually with current price quotations.

The application of any cost estimating method is closely related to the work or cost breakdown structure in use by the design and procurement agency. The NATO system is described in reference 1.

A3.3.2 Ship Cost Estimating

A3.3.2.1 Top-Down - Parametric

Method Name	Top-Down - **Parametric**
When to Use	During early concept design and if reliable historic data is available
Method Summary	The top down approach combines cost elements into groups and estimates these group costs by comparison with data from previous similar projects. The historic cost data is dated to associated technical parameters or cost drivers, by means of empirical relationships known as Cost Estimating Relationships (CERs). CER = f(parameter 1, parameter 2, etc.) It is important that the dependent parameters are selected so as to have a logical physical basis for example cost of hull structure would be expected to be related to weight of material and perhaps be qualified by construction standards. There are two types of CER • **Analogy CER** These are derived from data for a specific ship • **Regression CER** Derived from a best fit to data from several ships Once the CERs have been derived then the technical parameters of the new project can be inserted into the CERs and the new costs obtained. There are thus four steps in implementing the Top Down approach • Data Collection It is a prerequisite of the method that a database of past projects that are comparable to the new design exist. The data must be organised using the same, work breakdown structure. • Data Analysis The key to success of the method is the correct identification of appropriate cost driver parameters. Experience and judgement are essential. When analyzing data automatically it is quite likely that good correlations may be achieved with inappropriate parameters. This must be avoided.

Method Summary (continued)	• **Development of CERs** Generally regression techniques are used to establish equations relating the cost drivers to the known costs. The equations should be kept as simple as possible and the limits of their application clearly defined. • CER **Application** It is important that CERs are not used to estimate the costs of projects that have cost drivers outside of the range of the data from which the CERs were originally derived. Occasionally they may be modified if the new design has some clearly understood difference and its cost implications are obvious.
Advantages	• High level of technical definition is not needed • Easily applied manually or built into computer programmes • Very quick to apply • Can he applied at all levels of a Work Breakdown Structure if required • Unlikely to miss cost elements both physical and non physical as they are inherently swept up in the high level groupings • Inherently captures the effect of risk and other uncertainties
Disadvantages	• Can not give high accuracy • Does not cater for innovative solutions that differ from previous practice • Generally does not incorporate the effects of learning and other progressive improvements
Example	**Analogy CERs** These are generally of the form Cost = K x parameter If the hull plating cost of an existing ship was C, and the cost is assumed to be proportional to the plating weight W_e then the Cost of the plating for a new ship C_n with plating weight W_n is given by $C_n = \frac{C_e}{W_e} \times W_n$ This linear relationship can be modified so that a power law is incorporated $C_n = C_e \times \frac{W_n^a}{W_e^a}$ where a is a constant

Example (continued)	Regression **CERs** Regression equations can be constructed using more than one dependent parameter and can be derived using multiple linear regression techniques to give equations of the form $cost = axP_1^b + cxP_2^d + exP_3^f$ etc. where **a,b,c,d,e,f** are constants P_1, P_2, P_3 are technical parameters
References	**3,4,5,6**

A3.3.2.2 Bottom-Up - Detailed

Method Name	Bottom-Up - Detailed
When to Use	When a high level of technical definition is available and high accuracy is required
Method Summary	The approach used is to build up an overall cost by considering the cost of each individual item identified in the lowest levels of a work breakdown structure. This requires several elements to be successful - Work Breakdown Structure This is used to ensure that nothing is left out. - Detailed Technical Definition This will comprise a reasonably complete specification for the ship comprising an equipment list and drawings of the structure and layout. - Build Programme and Strategy The build sequence and times will need to be established. This latter will be derived in conjunction with the next two elements. - Equipment/Material Casting and Sourcing Quotes for equipment supply and delivery timescale will need to be obtained. - Labour Estimates The manhours needed to design, draw and construct the vessel will be estimated. This may be done in a bottom up manner through definition of every task or by a CER approach as described previously. - Overall Cost Estimation The final cost will be built up by applying appropriate rates, overheads and contingencies etc. to all the elements and summing. The method is manually intensive and the only automation practicable is through the use of general purpose computer tools such as spreadsheets and databases.
Advantages	- The most accurate approach provided sufficient data is available - Can more easily cater for a unique product for which no past data exists that can be used in a CER method.
Disadvantages	- Not suitable for early design - If the method is applied too early in the design process then it will generally lead to an underestimate through the omission of items - Prone to error because of the scale of effort needed to implement it - Costly and time consuming to apply - Overall cost is only known when design work is complete so feedback into the design is limited - Bottom up labour estimates are very difficult to generate and are often inaccurate
References	7

A3.3.3 Life Cycle Costing

A through life costing method is designed to calculate the total cost of ownership of a warship system from concept through to disposal. The elements to be covered will include (reference 1).

- The Programme Acquisition cost made up of
  - Design
  - Development
  - Software
  - Technical data
  - Publications
  - Support equipment
  - Training equipment
  - Initial spares
  - Facility construction
  - Project lead ship over cost
  - Multi national project management
  - Sailaway cost
    - Project management
    - Hardware
    - start up tooling
    - Allowance for changes
    - Test and trials
    - Initial outfit

- The operating and support costs covering the following
  - Personnel
  - Consumables
  - Direct maintenance
  - Sustaining investment, including spares and refits
  - Direct costs
    - Technical services
    - Documentation
    - Transport
    - Storage
    - Trainers and simulators
    - Facility fees
    - Helicopter operation
  - Indirect costs
    - Support equipment
    - Personnel training
    - Training facilities
    - Test sites
    - Support installations and personnel
    - command
    - support logistics

- Load out items cost

- Disposal costs

Various methods are available, generally built into one or more software packages. They are however all made up of several common elements each dealing with a specific aspect of the total cost. Typically these elements will include

- **Level of Repair Analysis**
  Equipments can be repaired and put back into service in many ways such as
  - Component repair on board
  - Component replacement and ashore repair
  - Removal and return to depot for repair
  - Removal and return to manufacturer for repair

  In each case there are costs associated with
  - On board and base spares holdings
  - Test and support equipment
  - Transport costs
  - Labour costs

  Level of repair analysis is designed to establish the costs associated with a particular repair philosophy, ie. whether repair is at assembly, module or part level and whether items are repaired on board, ashore, at a depot or returned to a manufacturer. The analysis will need to consider numbers of
  - Each equipment per ship
  - ships
  - Simultaneous theatres of operation
  - Repair depots and their location
  - Supply sources and their location

  The methodology may be extended to include an optimisation process that will perhaps minimise spares costs, maximise availability or improve some other factor.

- **Availability, Reliability and Maintainability**
  These analyses are performed in conjunction with level of repair analyses and operational effectiveness studies. The latter will use availability and downtime data and assess their effect on the overall operational scenario. Various approaches and techniques are used and could include
  - Failure Mode and Effect Analysis
  - Fault Tree Analysis
  - Markov Analysis

- **Manning Analysis**
  Crewing and support personnel costs will need to be identified.

- **Training Needs Analysis**
  Training and associated equipments costs may have to be identified and considered,

- **Operational Modelling**
  Operation of the vessel and it's systems will incur costs. These will include such factors as
  - Fuel
  - stores
  - Ammunition and other expendable equipments
  - Attrition through combat or accident

  Obviously these costs will be heavily dependent on the scenarios envisaged particularly if allowance is to be made for operational losses. It is important that these factors are also considered in any operational modeliing and analysis used to calculate MOEs and benefits.

A3.3.4 Investment Appraisals

In many ways an investment appraisal on its own is similar to a COEA except that there is fir more emphasis on the cost side of the equation. Generally both costs and benefits are converted into the same financial terms as in a traditional cost benefit analysis. If this is not possible then the costs of achieving the same level of benefit, or effectiveness, by means of different options is considered. In either case the purpose of an investment appraisal is to present the financial implications of alternative projects in a way that allows direct comparison between them. This is necessary because each project is likely to involve different spend profiles and so the effects of inflation and investment rates, etc., need to be determined. The techniques of investment appraisal are therefore directly relevant to the implementation of a COEA in its widest sense.

An investment appraisal will involve the following steps (reference 8).

- **Define the objectives**
  These must be defined in terms which bound the problem and can be measured and compared. At the same time it is important that they are not defined in a way which excludes the consideration of potential options.

- **Consider the options**
  A reasonable range of options should be considered. There are some important factors to he considered in defining the options.
  - The options should include the status quo or 'Do Nothing' option or if this is not practicable the 'Do Minimum' option.
  - Any external constraints which prevent the consideration of a possibly more cost effective option should be identified.
  - There should be sufficient options to wver the possible wst or benefit range.

- Identify, quantify and value the costs, benefits and uncertainties
  The factors to be considered will include
  - Acquisition costs. These should not include costs already committed or 'sunk' costs.
  - Operating costs including the costs of any assets that are involved in the operation of the option under consideration. These can be costed by assessing their value in their best alternative use. The length of operating life considered should be sufficient to identify any differences between options.
  - Disposal costs including any residual values.

  The costs should be expressed in terms appropriate to the price level pertaining when the appraisal is carried out. However, the time period during which tbe costs or benefits will be realised must be identified. In this way the effects of inflation etc., can be eliminated. It is important to recognise that the price increase rates for different elements may vary. Any assumptions used in making the estimates must be consistent with higher level planning and other projects.

- **Convert** financial **costs** and benefits to comparable **basis**
  Expenditure generally comes earlier than when benefits are realised, eg. spending more on initial acquisition may result in lower operating costs. However money spent early on has a higher value than the same amount received later because it may have been invested and so increased in value. Various mechanisms are used to deal with this.

- **Discount** Rate

This is applied to the costs and benefits. It **defines how the** value of money falls away with lime. It allows for the effects of inflation and interest rates on the future value of money but its value is determined primarily through a judgement of risk.

$$V_0 = V_n.D_n$$

and $$D_n = 1/(1+r)^n$$

where D_n = Discount factor
n = Year number
r = Discount rate
V_0 = Value at year 0
V_n = Value at year n

For example if a discount rate of 6% is assumed then 1 cost unit in a year's time is equivalent to 0.943 units now **(1/1.06).**

- **Net Present Value**

If both costs and benefits can be discounted to **the** same **date** then the difference between **them** is defined as the Net Present Value **(NPV).** This can be used as the basis for comparison between options. The NPV should be positive.

- **Equivalent Annual Costs**

These are useful when capital assets are considered or options with different lifetimes. They are derived by assuming the discount rate (defined above.

$$A_n = r/(1-D_n)$$

where A_n = Equivalent annual cost
D_n = Discount factor
n = Year number
r = Discount rate

For example if a discount rate of **6%** is assumed then a sum of 100 units now is equivalent to IO annual payments of 13.59 units starting a year from now. If different options have different lifetimes then **it is** important to consider what happens in the **period** after the shorter lifetime option has expired, ie. what the costs and benefits of following actions should be.

- **Internal Rate of Return**

The internal Rate of Return **(IRR)** is the discount rate at which the NPV becomes **zero.** If options **are to** he compared using **the IRR** as criteria **it** effectively applies a lower weighting to longer term **costs** and benefits. The IRR is the value of r that satisfies the following equation

$$0 = B_0 + B_1/(1+r) + B_2/(1+r)^2 + \ldots + B_n/(1+r)$$

where B_n = Net benefit in year n
n = Year number
r = Discount rate

- **Payback Period**
  This is defined as the time required to repay the original investment. As a basis of comparison it is limited in that it does not directly account for the timing of benefits and does not consider costs and benefits accruing after the payback date.

  Generally the benefits cannot always be converted to financial terms and so they need to be explicitly presented. In addition the cost profiles are usually required in order for a decision to be made. Normally there will be different values for costs and benefits corresponding to different sets of assumptions. it is also normal to break down the contributing elements in order to provide more information and explanation.

- **Consider uncertainties**
  As in all analyses the effects of uncertainties and the resulting assumptions should be examined by means of sensitivity analyses. This is more fully described in Section A3.5.

- **Assess balance between options**
  If all parameters can be expressed in the same terms the ranking of options is straightforward. However, generally there will be a wide range of factors to be considered and more complex selection mechanisms will be needed. Appropriate methods are described in Section A3.7.

- **Present results**
  The process by which data was developed should be recorded and its context explained. This will allow later evaluation of the completed project and feedback into future decision making processes.

A 3 . 3 . 5 References

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A3.4 TIMESCALES

A3.4.1 Introduction

This section does not attempt to describe methods for the estimation of project timescales or schedules as these are well documented in the project planning field (references 1, 2 and 3). Instead it illustrates how consideration of timescale effects can influence the parameters that are input to a COEA. The ways in which estimates of how timescales are themselves influenced by factors such as risk and uncertainty are described in Sections **A3.5** and A3.6 respectively.

Military system procurement timescales can influence the results of a COEA both directly and indirectly, and they can produce an impact on both costs and benefits

A3.4.1.1 Effect on Costs

Procurement programme costs are affected hy the programme timescale in several ways.

- Indirect costs
  These are the overheads that have to be supported continuously and are directly proportional to the timescale. In the case of production this will cover the costs of such items as
  - Facilities
  - support staff

  Similarly the operators will be faced with their own infrastructure and personnel charges covering the support elements for the system.

- Direct costs
  If a project extends in time it is often the case that more effort will be expended in total.

- **Maintenance of obsolete system**
  There may he cost and other implications through the need to keep existing systems in service longer until the new system is available.

- **Cash flow**
  The timescale will directly affect the cash flow. There is often an advantage in extending the timescale in order to spread the costs and avoid a high peak cost. However, if any superseded systems are to be sold when the new system is operational then the financial benefit of the sale will also be delayed. All these factors will have to be considered in, an investment appraisal.

A3.4.1.2 Effect on Benefits

The in service date will determine when the benefits of a new system are obtainable. Since the benefits are considered **in the** wider military context the timescales of system procurement have to be matched to an overall procurement programme that is designed to maintain a balanced military capability. Slippage in one programme could therefore affect the realisation of benefits from another..

A3.4.2 **References**

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A3.5 UNCERTAINTY

A3.5.1 Introduction

Uncertainty **is** when the probability of an event or outcome occurring cannot be defined.

In any estimate or prediction there **is** a degree of uncertainty over the exact value of the quantity concerned. The purpose of uncertainty analysis therefore is to:

- Determine bounds on estimates.
- Determine effects of uncertain estimates,

There is no attempt to assess the likelihood of particular estimate values.
There are thus two basic stages to be considered.

A3.5.2 Estimate Analysis

During this phase the basis of the estimate should be carefully examined. It is not sufficient to merely apply an arbitrary tolerance. A careful analysis will include consideration of the following factors:

- **Assumptions**
  All estimating procedures by their very nature involve the making of assumptions. The implications of these beiig incorrect should be examined.
- **Base Data Validity**
  Most estimates are based on data from previous projects. This data will itself have certain inaccuracies inherent in it. These may be due to measurement errors or other shortcomings in the collection methods employed.

The output **from** this **phase** will be a bounding of the range of the real value of the estimation. This should not merely be an arbitrary percentage but a reasoned judgement.

A3.5.3 Sensitivity Analysis

The sensitivity of the final measure of interest to variability in its component elements should be established. If there is no information on the likelihood of particular values then this must be performed by systematic variation. if the **estimate** analysis has produced a distribution of values then a more thorough probabilistic analysis may be performed. The methods to be used for sensitivity analysis will also be strongly influenced by the purpose for which the estimate was prepared. For example:

- **Measures of** Performance
  These values **are** likely to be used in simulation models to determine measures of effectiveness, (Section A3.2). In practice sensitivity will be determined by systematic variation.
- **Costs**
  The net effect of uncertainty in particular **cost** elements can be **treated** in the same way as the risk of external factors affecting the costs,
- **Timescales**
  Variation in times for particular project elements can lead to changes in critical path as well as changes in overall time.

A3.5.4 References

None available.

A3.6 RISK

A3.6.1 Introduction

Risk is simply defined as beii a combination of both the likelihood of an event occurring, and it's impact (reference 1). It differs from uncertainty analysis in that event probability is predicted.

Risk = f(Likelihood, Consequences)

where

Likelihood = The probability of occurrence
Consequences = The result of the event occurring

The event itself is usually, but not necessarily, considered as being an adverse event and is generally classified under one or the other of the following headings

- **Performance**
  Risk here refers to the potential non achievement of measures of performance. This could also include such factors as safety. It may be influenced by scientific or engineering development problems or by difficulties in production.

- **Cost**
  Cost risk is generally taken to be concerned with overruns of budget. They may he considered in strict financial terms or by some other commercial or political measure. A wide range of factors to be considered could include, component availability, supplier viability, exchange rate changes etc.

- **Timescale** or Schedule
  Risks to timescale that actually occur usually result in programme overruns. This could be caused by development problems, material or labour shortfalls or even external causes outside the project's control.

These three risk areas are often heavily interdependent, for example failure to meet performance may well result in further delays and expenditure in rectifying the problem.

Risk is of course a factor that changes throughout a project's life. Most procurement processes are designed to reduce the risk inherent in a project at it's inception. It is generally necessary to take risks in order to exploit opportunities and so most risk analysis methods are closely linked with processes intended to actually manage the risk component of a project. A representative risk management approach will include the following stages

- **Identification**
  During this stage the component elements of the project will be defined and any risks associated with them identified.

- Analysis
  The analysis stage evaluates the consequences of the risks occurring on the overall project and thus provides data to be used in subsequently controlling them in subsequent stages.

- **Planning**
  During this stage contingency plans will be made and any corrective actions and risk reduction measures identified.

- **Management**
  This is the implementation stage where risk reduction or mitigation occurs and continuous monitoring and reanalysis performed.

Risk is usually an important element in option selection decisions and so the first two stages, Risk Identification and Analysis will need to be carried out as part of any decision process. There are various methods of analyzing risk in acquisition projects. These can be broadly divided into

- **Qualitative**
  These methods make little or no attempt to assign numerical values to the likelihood or consequences of particular risks manifesting themselves. Their application relies heavily on judgement and experience but they do however provide a valuable framework for managing risk and can act as a precursor to more detailed quantitative analysis.

- **Quantitative**
  These approaches represent the next stage after qualitative analysis has been performed. Given variability in the constituent elements of a final estimate, typically total cost or project duration, these methods produce the probability distributions of the final result that can be expected.

The results can be incorporated into an evaluation process in several ways. The qualitative risk identification process supports the application of subjective judgement whilst the results of a quantitative analysis could be used directly by means of a 'most likely' value. In both cases however, sensitivity analyses utilising possible consequences of particular events should also be performed. Using these approaches the results of risk analyses can be incorporated into the Cost Effectiveness methods described in a later section.

A 3 . 6 . 2 **Qualitative**

Qualitative risk analysis methods rely heavily on the experience and judgement of the analysts and any documentation and control needs to be integrated as part of the Risk Management approach.

A3.6.2.1 **Risk Registers**

Method Name	Risk Registers
When to Use	When quantitative data is not available, early in the programme
Method Summary	Qualitative methods are used primarily as a project management tool and they all follow the same general pattern and involve the following steps - Project Definition The activities within the project are defined. - Risk Identification Any potential risks to the project are identified by means of interview, brainstorming etc. This process relies on past experience. An assessment of the relative likelihood is also made. This is usually expressed in simple scale terms such as - Low - Medium - High These risks are documented on a register which becomes the monitoring record in a risk management procedure. - Riik Classification The area affected by the risk is determined. This may be one or more of - Performance - Cost - Timescale It can be argued that all risks have an ultimate impact on cost as both performance and time can be converted to financial terms. Failure to meet specified performance is often linked to liquidated damages or even rejection. Similarly time overruns may be penalised contractually. In any case an increase in time will involve increased costs either through continued use of direct labour and facilities or through the project's share of general overheads. - Impact Assessment An assessment is made of the consequences that would arise if the identified risk should actually occur. This may be expressed in qualitative terms as follows - Low - Medium - High - Riik Evaluation The evaluation of risk as a combination of likelihood and impact is performed in qualitative terms by means of a table as shown.

Method Summary (continued)	**Risk Evaluation Table**

Impact	Likelihood		
	Low	Medium	High
High	Critical	Unacceptable	Unacceptable
Medium	Significant	Critical	Unacceptable
Low	Minor	Significant	Critical

- Risk Mitigation
  The effects of actions taken to mitigate the risk may themselves result in secondary risks being identified. These too must be assessed in a similar way.
- Risk Contingencies
  As an alternative to taking action to eliminate the risk, contingencies may be put in place to cover the possibiiity of the risk occurring.

Advantages	• Easily applied • Valuable project risk management technique • Can be applied early in programme when benefits are highest
Disadvantages	• Reliance on subjective judgements • No quantitative data available for further analyses • Difficult to assess whole programme risk, therefore cannot really compare overall programmes • No visibility of possible high risks resulting from combinations of risks in several elements.
Example	A typical risk register format would be as follows **Risk Register**

Risk Register			
Risk Identifier			
Date			
Description			
Impact Performance Cost Timescale			
Likelihood	High	Medium	Low
Mitigation			
Contingency			

References	1

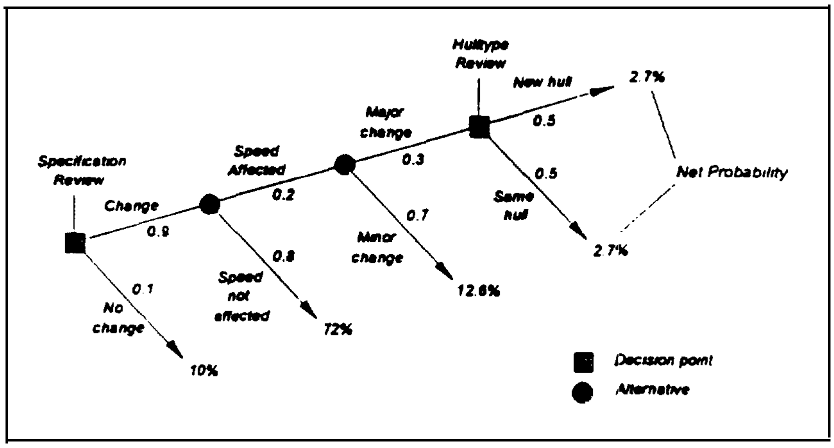
A3.6.3 Quantitative

Various quantitative techniques exist.

A3.6.3.1 Probability/Decision Trees

Method Name	Probability/Decision Trees
When to Use	Early in a project for dealing with high level contingency planning. The method assists in project structuring and planning for particular risks occurring and provides a vehicle for assessing the overall probability of particular outcomes.
Method Summary	The basis of the method is to chain together logical sequences of uncertain or chance events. At each event different outcomes are assigned a probability level. The sum of the probabilities branching out from each event totals 1.0. In this way a probability tree is constructed that assumes statistically independent probabilities for each event. The method is modified if some of the nodes become decisions rather than events. In these cases the probability of the decision itself is 1 .O even though the outcome may have several different results with their associated probabilities. In both cases the probability of particular net outcomes is found by combining the probabilities along the appropriate branches of the tree. Once the probabilities of particular outcomes have been determined then the various consequences can be evaluated and a probabilistic assessment of the overall outcome of the project made. This method can be extended to a Markovian approach whereby the occurrence of events causes a change of state (reference 2) but the extra complexity is probably not matched by the availability of suitable data and the assumptions of event independence may become invalid.
Advantages	• Simple approach suitable for early contingency planning and budgeting;
Disadvantages	• Only really suitable for early high level project assessments with limited complexity • Assumes statistical independence between events • Lack of base data on which to base probability assessments • Uses assessments of probabilities that generally rely heavily on subjective judgements
Example	During the concept design phase of a patrol vessel project there is a strong, 90%, likelihood of specification changes being made and a 20% chance that a given change will affect the speed requirement. Such a change will certainly require a change of engine and if the speed change is significant then this will require the consideration of a new hull form with a consequent large increase in cost.

<table>
<tr><td>Example
(continued)</td><td>



<u>Project Decision Tree</u>
In this case there is a 2.7% (0.9 x 0.2 x 0.3 x 0.5 x 100%) risk that an alternative hull form with it's associated redesign costs will need to be considered. Similarly there is a 72% chance that the specification change will not affect the speed.
</td></tr>
<tr><td>References</td><td></td></tr>
</table>

A3.6.3.2 Controlled Interval and Memory

Method Name	Controlled Interval and Memory
When to Use	When quantitative data is available for timescale variability
Method Summary	This approach assumes that the possible duration of each activity in a network is defined by a set of 'intervals' each being assigned a particular probability. The sum of all the probabilities for an activity equalling unity. In order to compute the duration probability distribution of two sequential activities each possible duration of the first activity is used to define the start date for the second activity. For each of these start dates there will of course be a resulting end date distribution based on the probabilities of the second activities duration. In this way a complete range of durations for the two activities can be computed. The shortest overall duration would be that corresponding to both activities taking the shortest time. This process is repeated throughout the network and so each end point will have a range of completion dates and associated probabilities. The amount of computation needed is determined by the complexity of the network and the size of the intervals used. The calculations can be simplified if the same sized or 'common' interval is used throughout the network. The process can be modified to take account of dependent activities where the duration distribution of one is dependent upon the duration of the first. This is described in reference 1.
Advantages	• Can be performed without use of computer software if a common interval is used to simplify the calculations - Sensitivity analysis possible
Disadvantages	• Lack of base data on which to base assessments of probabilities • Able to deal with simple networks only
Example	Given two activities A I and A2 with duration distributions defined with common intervals as shown Activity Probabilities

Duration (months)	Duration (months)	Probability
Activity A1		
2.5-3.5	3	0.3
3.5-4.5	4	0.5
4.5-5.5	5	0.2
Activity A2		
1.5-2.5	2	0.4
2.5-3.5	3	0.6

Example (continued)

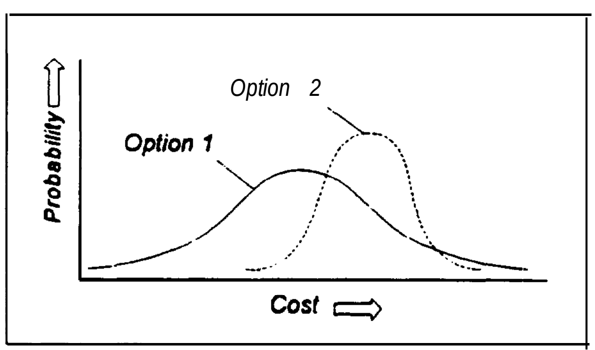
The probability distributions for the combined interval is computed as follows

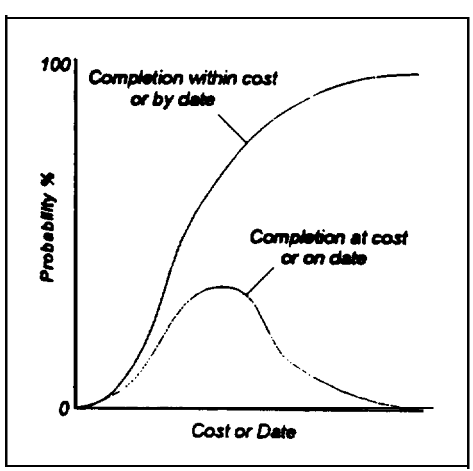
Combined Probability Calculation

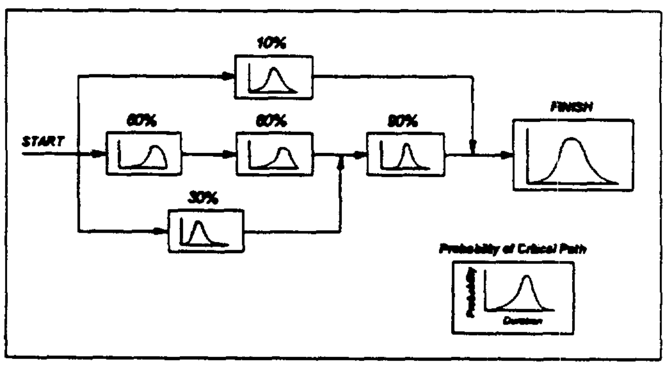
Total Duration (months)	Calculation	Probability
5	(0.3 x 0.4)	0.12
6	(0.3 x 0.6)+(0.5 x 0.4)	0.38
7	(0.5 x 0.6)+(0.2 x 0.4)	0.38
8	(0.2 x 0.6)	0.12

References	2

A3.6.3.3 Monte Carlo Modelling

Method Name	**Monte Carlo Modelling**
When to **Use**	When quantitative data is available for cost and timescale variability
Method Summary	These methods have been adapted for use with **both** cost and project **timescale** data. They all rely on applying a statistical distribution to any estimates of time or cost associated with the project. • **Cost Estimations** The method is applied as follows • **Cost Item Identification** All cost elements are **identified in the** normal way according to a suitable work breakdown structure. • **Item** Cost **Variation** For each cost **item** a distribution of values **is** defined ranging from an absolute minimum to a **worst** case maximum. The actual distribution **may be a simple** triangular one using the minimum and maximum values, together with the most likely, or it may be defined by a standard distribution such as the normal or a skewed function. • **Simulation** Once the possible cost item value functions have been defined a numerical simulation is run repeatedly. For each item a random number generator modified to fit the selected distribution is used to generate a cost value. All the individual items are then summed to give the overall cost. This process is repeated many times until a distribution of total cost values is generated. Inspection of this distribution will allow a **judgement** to be made on the most likely cost and the probability of variation from that **cost.** Comparison of these curves for different project options may aid selection decisions as shown. Expected Cost from Simulation 

Method Summary (continued)	**Timescale** Estimations In applying the method to timescale estimations the principles are the same as for cost estimation. However the implications are complicated by the interdependencies between activities in any real project. The method is applied as follows - **Activity Identification** Conventional project activity networks are constructed using anticipated activity durations and interdependencies. From this Critical Path Analysis will determine the planned completion date. - **Activity Timescale Variation** Each activity **is** then assigned **a** distribution1 of timescales ranging from the minimum possible to the worst case maximum. The distribution of times is defined by a selected statistical function. - Decision Points If activity times vary then it is likely that activity interconnections will also change. Some computer models allow the incorporation of such conditional decisions into the network model. - **Simulation** Once the possible activity timescale functions have been defined a numerical simulation is run **repeatedly.** For each activity a random number generator **modified** to fit the selected distribution is used to generate an expected duration. The network is then reevaluated to determine the new critical path and an overall project duration is calculated. After repeated runs various statistics describing the distribution of project duration, probable critical paths etc., will be available. A **typical** presentation is shown Cost/Timescale Probability Plot 

Method Summary (continued)	A variation on the Monte Carlo method is Latin Hypercube. Latin Hypercube sampling changes the way assumption values are generated during a simulation. This method works by segmenting the assumption's probability distribution into a number of non-overlapping intervals, each having equal probability. Then, from each interval, a value is selected at random according to the probability distribution within the interval. This collection of values forms the Latin Hypercube sample. Latin Hypercube Sampling is generally more precise for producing random samples than conventional Monte Carlo sampling because the full range of the distribution is sampled in a more even and consistent manner. Thus, with Latin Hypercube Sampling, a smaller number of trials is required to achieve the same accuracy. The added expense of this method is the extra memory required to hold each assumption's sample while the simulation is running. When all the values from each sample have been used, a new batch of samples is generated.
Advantages	• Provides quantitative data for further analysis - Generally relatively insensitive to detail variations in estimated probability distributions - Sensitivity analysis possible and inherent in method
Disadvantages	• Input data is only approximate • Model structure can become extremely complex if conditional decisions are incorporated • Lack of base data on which to base assessment of probability distributions - Contingencies often built into 'expert' estimates
Example	A small project is made up of 5 activities arranged over time as shown. Each has a probability distribution associated with its expected duration. When a Monte Carlo simulation of the project is run, an overall expected duration distribution results together with the likelihood of each activity being on the critical path. <u>Expected Project Duration and Activity Criticality</u> 
References	1

A3.6.4 References

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A3.7 MULTI CRITERION DECISION MAKING

A3.7.1 Basic Decision Making

When a formal decision is required but information is limited to a single variable such as measures of effectiveness, there are some simple decision criteria which may be used to help the decision maker in his task. Their apparent trivial nature does not make them any less valid as decision criteria. It is just that, in general, the amount of information available requires a more sophisticated method to be employed.

The reader will notice that the three basic decision criteria shown here have each produced a different recommendation. This is not necessarily a bad thing but simply reflects different biases. It is up to the decision maker to select the most appropriate criterion to use for the circumstances surrounding the decision.

A3.7.1.1 MaxiMax Decision Criterion

<table>
<tr><td>Method Name</td><td>MaxiMax Decision Criterion</td></tr>
<tr><td>Method Summary</td><td>This decision criterion is based on an optimistic viewpoint and recommends the option which has the best of the best possible outcomes i.e. Maximize the Maximum benefit (Measure of Effectiveness).</td></tr>
<tr><td>Advantages</td><td>• May lead to the best outcome.</td></tr>
<tr><td>Disadvantages</td><td>• Does not take into account avoidance of negative outcomes.</td></tr>
<tr><td>Example</td><td>Three mine counter measures vessel designs are proposed: d_1, d_2 and d_3. Predicted measures of effectiveness (clearance level) have been established in two scenarios S_1 and S_2. The information is summarised in the following table.

Assuming that the relative likelihoods of S_1 and S_2 occurring are not known, then the MaxiMax approach will recommend that the design d_1 is selected since that design gives the best possible level of performance. (79% clearance)

<table>
<tr><td></td><td>S_1</td><td>S_2</td></tr>
<tr><td>d_1</td><td>79%</td><td>58%</td></tr>
<tr><td>d_2</td><td>75%</td><td>60%</td></tr>
<tr><td>d_3</td><td>65%</td><td>73%</td></tr>
</table>
</td></tr>
<tr><td>References</td><td>1, 2, 20</td></tr>
</table>

A3.7.1.2 Maximin Decision Criterion

Method Name	**Maximin Decision Criterion**
Method Summary	This decision criterion is based on a **pessimistic** approach and recommends the option which has the best of the worst possible outcomes i.e. Maximize **the Minimum benefit.**
Advantages	- **Avoids the worst outcomes.**
Disadvantages	- **Does not take into account pursuit of beneficial outcomes.**
Example	Three mine counter measures vessel designs are **proposed:** d_1, d_2 **and** d_3. Predicted measure of **effectiveness (clearance** level) have been established in two scenarios S, and S_2. The information is **summarised** in the following **table.** Assuming that **the** relative likeliioods of S, and S_2 occurring are not known, then the **Maximin** approach will recommend that the design d_3 is selected since this will ensure that there is no possibility of getting worse than a **65%** clearance level. Both of the other decisions may lead to lower clearance levels.
References	**1, 2, 20**

	S_1	S_2
d_1	79%	58%
d_2	75%	60%
d_3	65%	73%

A3.7.1.3 <u>Hurwicz Alpha Decision Criterion</u>

<table>
<tr><td>Method Name</td><td>Hurwicz Alpha Decision Criterion</td></tr>
<tr><td>Method Summary</td><td>
This decision criterion is a compromise between the optimistic and pessimistic approaches of the maximax and maximin criteria.
It achieves this by using an optimist-pessimist coefficient, Alpha α. α varies between a value of 0 for the extreme pessimist lo 1 for the extreme optimist.
in order to make a decision a new score value is determined as follows
Score = a (highest benefit) + (1 - a) (lowest benefit)
The resulting score then determines which option is selected.
</td></tr>
<tr><td>Advantages</td><td>• It is a compromise solution</td></tr>
<tr><td>Disadvantages</td><td>• It is very difficult to determine a value for a.</td></tr>
<tr><td>Example</td><td>
Three mine counter measures vessel designs are proposed: d_1, d_2 and d_3. Predicted measure of effectiveness (clearance level) have been established in two scenarios S_1 and S_2. The information is summarised in the following tahle.
<table>
<tr><th></th><th>S_1</th><th>S_2</th></tr>
<tr><td>d_1</td><td>79%</td><td>58%</td></tr>
<tr><td>d_2</td><td>75%</td><td>60%</td></tr>
<tr><td>d_3</td><td>65%</td><td>73%</td></tr>
</table>
If a value of a of 0.7 is selected, ie. a reasonably optimistic view is taken then the scores for each option can he calculated as follows
Score d_1 = (0.7 x 79%) + (0.3 x 58%) = 72.7%
Score d_2 = (0.7 x75%) + (0.3 x602) = 70.5%
Score d_3 = (0.7 x 73%) + (0.3 x 65%) = 70.6%
In this case design d_1 is selected as it has the highest resulting score.
</td></tr>
<tr><td>References</td><td>20</td></tr>
</table>

A3.7.1.4 MiniMax Regret Decision Criterion

Method Name: **MiniMax Regret Decision Criterion**

Method Summary: This decision criterion does not assume a purely pessimistic or optimistic result but attempts to minimize the possible regret associated with a decision. Regret here means the additional benefit that could have been gained if an alternative decision had been made, given the scenario which occurred.

Advantages:

- Avoids the worst outcomes.

Disadvantages:

- Avoids the best outcomes.

Example:

Three mine counter measures vessel designs are proposed: d_1, d_2 and d_3. Predicted measures of effectiveness (clearance level) have been established in two scenarios S_1 and S_2. The information is summarised in the following table.

	S_1	S_2
d_1	79%	58%
d_2	75%	60%
d_3	65%	73%

To determine the optimum decision using the Minimax Regret criterion, it is first necessary to establish the regret associated with each decision and scenario. This is achieved by calculating the difference between the performance of each decision and the performance for the best decision that could have been taken for that scenario.

eg.1 The regret for d_2 if S_1 occurs is 79% - 75% = 4%, since d_1 would have been 4% better.

eg.2 The regret for d_1 if S_2 occurs is 73% - 58% = 15% since d_3 would have been 15 % better.

Continuing this procedure produces a regret table shown opposite. It is finally necessary to apply the Minimax Regret criterion by Minimizing the Maximum Regret for each decision. This leads to the recommendation that d_2 is selected since this option ensures that the maximum regret is 13 %.

	S_1	S_2
d_1	0%	15%
d_2	4%	13%
d_3	14%	0%

References: 1, 2, 20

A3.7.2 Expected Value Criterion

The main failing with the methods described in the previous examples is that they do not take into account any information regarding the relative likelihood of the various outcomes occurring. This sort Of information will inevitably have an important effect on the decision process and its outcome. The most common way of introducing outcome probabilities into the decision process is by using the Expected Value (EV) criterion.

Put simply, the EV of a decision alternative is the sum of weighted benefits for that alternative. The weight for a benefit is the probability that the benefit will be achieved. The benefit in question is generally an objectively measurable value, typically a measure of effectiveness of the system.

Method Name	**Expected Value Criterion**
Method Summary	Several scenarios are generally postulated within which the system is to function. Measures of Effectiveness for the system operating within each of the scenarios are determined. If there is no further information available then either of the three basic decision criteria (Maximax, Maximin, Minimax Regret) may be applied. However, it is likely there will be a preference as to the liilihood of one scenario occurring over another. These preferences are represented as probabilities which are in turn used as the weights when adding up the scores for each option. The final score for each option is called it's Expected Value. The option that provides the highest score is the optimum decision and is therefore the one to be selected. The example below shows the Expected Value criteria being used in a relatively simple scenario. Generally, there are a large number of interrelated decisions to be made and many probabilities which need to be taken into account in the decision making process. The Expected Value criteria can still be applied to these situations but it is often useful to create a decision tree which helps to clarify the actual structure of the decision. A decision tree also helps to evaluate the mathematics of the situation. It should also be noted that the probabilities used with this method may be described as probability functions, so that a spread of expectations can also be taken into account.
Advantages	• The method is highly intuitive and it is readily apparent why the method recommends one option over another. The decision maker is therefore able to experiment with "what-if ?" scenarios more: easily. - Uses measures of effectiveness directly within the decision process. · Also allows the decision maker to include his knowledge and experience by estimating the likelihood of the various outcomes.
Disadvantages	• Tbemethod assumes that the value of an effectiveness parameter is linear in the sense that, for example, a mine counter measures vessel that produces a risk to subsequent shipping, half that of another is then twice as preferable. This is clearly not always the case.

Example	Three mine counter measures vessel designs are proposed: d_1, d_2 and d_3. Predicted measures of effectiveness (clearance level) have been established in two scenarios S, and S_2. The information is summarised in the adjoining table. | | S_1 | S_2 | | d_1 | 79% | 58% | | d_2 | 75% | 60% | | d_3 | 65% | 73% | Suppose that the vessel is more likely to be involved in S_1 operations than S_2 operations. This needs to be quantified into relative probabilities. For example, it may be suggested that $Prob(S_1)$ = 0.6 and $Prob(S_2)$ = 0.4. In other words, if two scenarios are available, the probability that the minehunter will be required to operate in Scenario 1 is 0.6 and the probability that it will be required to operate in Scenario 2 is 0.4. In this case, the Expected Value (EV) for each option is: $EV(d_1) = (0.6 \times 79\%) + (0.4 \times 58\%) = 70.6$ $EV(d_2) = (0.6 \times 75\%) + (0.4 \times 60\%) = 69.0$ $EV(d_3) = (0.6 \times 65\%) + (0.4 \times 73\%) = 68.2$ Evidently, decision d_1 is the correct option to select in this instance because this is the option which yield the highest expected value. Note that if the relative probabilities of the scenarios changed, then the: recommended option may also change to reflect the change in operational emphasis.
References	1. 8. 10. 16

A3.7.3 Complex Decision Making

In terms of overall Cost Benefit the benefit term is generally made up from several measures, usually Measures of Effectiveness, that represent different quantities. In order to reach a decision these different quantities must be aggregated in some way. There are various formal methods available to help the decision maker to perform this task and some examples are presented in this section.

A3.7.3.1 Multi-Attribute Utility Theory

In the previous section, the Expected Value criterion was examined and was used to help determine an optimum decision. Research has show that when measures of effectiveness are within bounds considered reasonable by the decision maker, the Expected Value is a good decision criterion to use. For extreme cases where, for example, there is a high risk, or where measures of effectiveness are very high or very low, the reliability of this criterion for producing good decisions breaks down.

As an example, when considering taking house insurance, the expected value for such a decision is negative, since the insurance companies need to make a profit. Therefore, monies paid into an insurance policy will exceed the expected return. The Expected Value criterion will therefore recommend that the decision maker does not take out an insurance policy! The fact that insurance is such a common phenomena shows than in certain circumstances it is not enough to talk about monetary value but rather to its utility which will permit the use of expected utility as a desirable decision criterion.

Utility can be defined as the measure of the total worth of a particular outcome and reflects the decision maker's attitude toward a collection of factors such as profit, loss and risk.

As previously mentioned, the concept of utility was introduced to take into account extreme and 'non-linear' preferences; for example where risk or uncertainty is involved, or when large monetary values are included. A special case of multi-attribute utility theory (MAUT) is known as multi-attribute value theory (MAVT). In this instance, it is assumed that the decision maker is neither a risk-taker nor a risk-avoider. Preferences are assumed to be 'linear' and the use of lotteries (see Method Summary) is avoided. The decision maker is simply required to state the value of two alternative systems, and the value of other systems can be easily interpolated or extrapolated From these. These values may then be used in place of utility in the remainder of the theory.

Method Name	Expected Utility Criterion
Method Summary	The mechanics of using the Expected Utility (EU) and Expected Value (EV) criteria are very similar but they differ in one important respect; the Expected Value criteria uses measures of effectiveness as the basis for decisions while the Expected Utility criteria uses values of utility derived from measures of effectiveness. The use of Expected Utility therefore requires the additional effort of deriving the utility values. Creating utility values from measures of effectiveness is a way of introducing the decision maker's subjective opinions into what is essentially an objective exercise. For example, the decision maker may well feel that an increase from 20% to 25% in a particular performance figure would be more beneficial than an increase from 90% to 95%, or that a performance figure of 30 units is more than twice as good as a system with a performance of 15 units.

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<tr>
<td>Method Summary (continued)</td>
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There are various alternative methods available for establishing the utility of a given value. The most common method involves engaging the decision maker in a hypothetical lottery. This method has the following steps:

Determine the minimum and maximum acceptable levels of performance within which all measures of effectiveness for the problem will lie.
Assign arbitrary values of utility to the two extreme measures of effectiveness (eg. U(Min) = 0, U(Max) = 100)
Determine the utility for each value by offering the decision maker the following option; either accept the system with it's specified level of performance or engage in the following lottery:
Obtain a solution with maximum performance with probability p or obtain a solution with minimum performance with a probability of (l-p).
For a measure of effectiveness midway between the minimum and maximum acceptable values, if p is close to 1 then the lottery will be preferred since there is a high chance of "winning" a system with the maximum performance level. If p is close to zero, however, the system will be accepted as it is, rather than run the risk of "winning" a system which has the minimum level of performance. There will be some value of p for which the decision maker has no preference between accepting the system as it is or of entering the lottery. This value of p is converted into a Utility Value using the following formula:
$$U(MOE) = (1-p) \times U(Min) + p \times U(Max)$$
where U(x) = the Utility of x
Once the Utility values have been calculated they are used in the same way as MOE values were used in the Expected Value criteria. i.e. The Utility values are weighted and added according to the relative likelihood of the various scenarios occurring. The option which has the highest Expected Utility value is the one which is recommended.

To make use of utility theory in a multi-attribute problem, it is first necessary to demonstrate that the conflicting attributes exhibit utility independence. In a two attribute (X and Y) situation, utility independence means that preferences for values of Y are independent of values of X. For example, consider a project whose two attributes are completion time and cost. The decision maker prefers the project to be completed in 2 years rather than 3 years, when the cost is M10. If the cost of the project is M20, the decision maker still prefers the project to be completed in 2 years. Similarly, it would be preferable to complete the project with a cost of M10 rather than M20, irrespective of the date of completion. The two attributes are therefore said to be mutually utility independent.
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Method Summary (continued)	If two or more attributes are not independent then in many circumstances, the interaction between the two is not strong enough to warrant finding an alternative course of action to the standard multi-attribute theory. In other cases it is often possible to transform the two attributes and perform the analysis on the new set. The new attributes must still capture the critical aspects of the problem and they must be measurable but in general, it is usually possible to find a suitable transform. By specifying the Utility independence of two or more attributes it is now possible to assume that tbe multi-attribute utility function for the dual-attribute case is now a function of the individual utilities. This may be represented mathematically as: $U(x,y) = f\{U_x(x) \times U_y(y)\}$
Advantages	▪ The method has all of the advantages associated with the expected value criterion, but eliminates that methods drawback of assuming linear value. MAUT does this by introducing the concept of utility to express peoples views of true value, risk *etc.*
Disadvantages	• The concept of utility is not necessarily an intuitive one to grasp. It is true that converting the values into utilities using methods such as the lottery offer can be a very cumbersome process if it is not used correctly.
Example	Three mine counter measures vessel designs are proposed: d_1, d_2 and d_3. Predicted measures of effectiveness (clearance level) have been established in two scenarios S_1 and S_2. The information is summarised in the adjoining table. (table: | | S_1 | S_2 | / | d_1 | 79% | 58% | / | d_2 | 75% | 60% | / | d_3 | 65% | 73% |) The decision maker decides that the minimum acceptable clearance level is 50% while the maximum is, of course, 100%. Utility values for these parameters are chosen arbitrarily so that: U(50%) = 0 U(100%) = 10 To determine the Utility of a value (say 79%), the following hypothetical offer is made to the decision maker: "Accept a guaranteed clearance level of 79% or enter the following lottery: A probability of 0.5 of getting 100% clearance or a probability of 0.5 of getting 50% clearance level". For this example, assume that the decision maker will prefer to take the guaranteed 79% clearance level, rather than run the risk of only getting a 50% clearance. The same question may now be asked but with a 0.95 probability of achieving 100% clearance and probability of 0.05 of getting 50% clearance. In this case, the decision maker will accept the lottery as there is every reason to suppose that a 100% clearance level will be achieved. This continues until, eventually, a value ofp will be reached where the decision maker is indifferent as to whether to accept the guaranteed value or enter the lottery. If, for example, the decision maker decides on a value of $p=0.85$, then the 79% clearance level is converted into a utility thus:

	S_1	S_2
d_1	79%	58%
d_2	75%	60%
d_3	65%	73%

Example (continued)

$$U(79\%) = 0.85 \times U(100\%) + 0.15 \times U(50\%)$$
$$= 0.85 \times 10 + 0.15 \times 0$$
$$\therefore \underline{U(79\%) = 8.5}$$

Repeating this process with the other values results in a Utility table shown opposite. These values are now used to determine the Expected Utility in the same way the measures of effectiveness were used to determine the Expected Value in the previous section.

	S_1	S_2
d_1	8.5	3.3
d_2	7.9	4.0
d_3	5.8	7.6

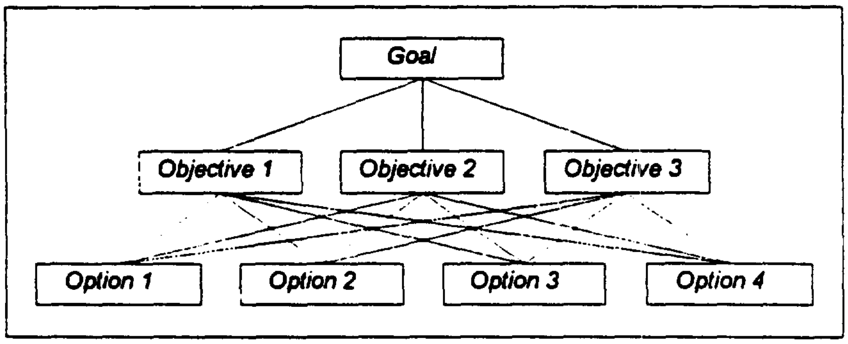
Again assuming that the relative probabilities of the two scenarios S_1 and S_2 are 0.6 and 0.4 respectively, the Expected Utility (EU) criterion gives:

$$EU(d_1) = (0.6 \times 8.5) + (0.4 \times 3.3) = 6.42$$
$$EU(d_2) = (0.6 \times 7.9) + (0.4 \times 4.0) = 6.34$$
$$EU(d_3) = (0.6 \times 5.8) + (0.4 \times 7.6) = 6.52$$

Decision d_3 is the option recommended by this criterion because it is the option which provides the largest value of utility.

References: *1, 2.4, 8.* 14, 16

A3.7.3.2 Analytic Hierarchy Process

Method Name	Analytical Hierarchy Process (AHP)
Method Summary	Most multi-criteria decision models require two steps; data gathering and computation. The first step may involve determining expected values or values of utility. The second computational step manipulates the values entered into the model to produce the optimum decision The AHP also involves these two steps. Perhaps one of the main contributing factors to the method's popularity, however, is in the relative simplicity of the data gathering stage and in the complexity of the computational stage. The two taken together probably lend a large psychological boost to a decision makers' reliance on the method. The problem is typically structured in a hierarchy as shown. The overall goal at the top and with a breakdown of various objectives on the intermediate levels. At the lowest level are the options under consideration. Problem Hierarchy  The interconnecting lines indicate where the weightings or preferences have to be established in order to produce an overall solution. In order to calculate these weights, data must be gathered from informed experts. **The data-gathering stage for the AHP differs from most other methods in that one option or criterion is not given an individual absolute score. Rather, two alternative options or criteria are compared pair-wise and a "score" for the relative importance of the two options assigned to that pair.** For example, when comparing two options A and B with respect to, for example, project completion time, the decision maker would be asked: "**Thinking only about** the project completion time, **which option do you prefer, A or B ?**"

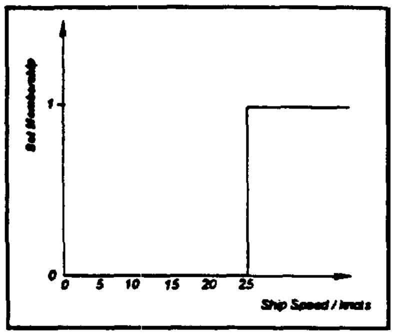
Method Summary (continued)	If there is a preference expressed, then the decision maker is further asked: "Indicate the strength of your preference for A over B (or vice versa) on the following scale: 1 Equally Preferred 3 Weak Preference 5 Strong Preference 7 Demonstrated Preference 9 Absolute Preference" The decision maker may select a verbal answer or respond with a numerical answer using intermediate values if requiredl. **Note: The scale** shown was suggested by Saaty, the original developer of the AHP. Other scales have been suggested and used successfully. This pair-wise comparison is repeated for all pairs of options and the results produce a matrix of responses. The AHP method assumes that preference is measurable on a ratio scale and that judgements are statements of relative preference. So, if A is preferred to B and the strength of preference is S, then the comparison of B with A is the reciprocal of that value, *i.e.* 1/S. The computational step for the AHP involves operating on the matrix to produce a vector of relative preferences. One common method involves converting the matrix into an eigenvalue and its associated eigenvector. The former value gives an indication of how consistent the decision maker's responses are, while the eigenvector itself shows the relative preferences of the options. The option with the highest score is selected. It should be stressed that the decision maker does not need to be aware of the mathematical mechanics of the computational process (they are usually performed by computer), nor indeed does he need to understand what eigenvectors or eigenvalues are. To trust the method, he must simply accept that the model has been validated many times and can be relied upon to produce sensible decisions. The complexity of the computational process means that it may not always be apparent why one option scored more than another option.
Advantages	• The main advantage of using the method is in the manner in which the information is gathered from the decision maker. Simple comparison of two alternatives and then gauging the extent of the preference is infinitely simpler than attempting to establish utility values for each proposed solution.
Disadvantages	• There are few, if any, intuitive steps involved in moving from a matrix of simple preferences to the final preference vector. Rationalizing the matrix is a complex, iterative process which bears little or no resemblance to our own mental decision making processes. Many decision makers are uncomfortable with this idea. • In most problems a very large number of comparisons have to be made. In some ways the questions may have become too simple.

Disadvantages (continued)	• The removal of one option or addition of another can sometimes cause the order of the remaining or existing options to change. • The inevitable inconsistencies in a large number of comparisons results in the output of a consistency index from the mathematical analysis (based on the eigenvalue). It is difficult to ascribe a significance to the magnitude of this index except to say that there are inconsistencies present. • There are problems in ascribing the weights on preferences. These values are ratios representing relative preference against a criteria.
Example	Five similar mine counter measures vessel designs (d_1, d_2, d_3, d_4 and d_5) have been proposed and various selection criteria have been identified. One of these (clearance level) has been used to create a matrix of preferences. This was performed by asking questions similar to those described in the method section above. For example, in response to "Thinking only about the clearance level, which option do you prefer, d_1 or d_2?" the decision maker may have a "Strong Preference" to d_2 thus making the (d_2,d_1) element in the matrix equal to 5 and the (d_1,d_2) element equal to 1/5. The final matrix may look like: $\begin{array}{c} \\ d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \end{array} \begin{array}{c} \begin{array}{ccccc} d_1 & d_2 & d_3 & d_4 & d_5 \end{array} \\ \begin{pmatrix} 1 & 1/5 & 1/9 & 1/3 & 1/2 \\ 5 & 1 & 1/5 & 5 & 5 \\ 9 & 5 & 1 & 9 & 9 \\ 3 & 1/5 & 1/9 & 1 & 1 \\ 2 & 1/5 & 1/9 & 1 & 1 \end{pmatrix} \end{array}$ Feeding this matrix into the "AHP Solver" will a reveal a normalised vector which indicates the relative preferences of the options. $\begin{array}{c} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \end{array} \begin{pmatrix} 0.04 \\ 0.22 \\ 0.61 \\ 0.07 \\ 0.06 \end{pmatrix}$ This vector reveals that the preferred option is option d_3 since this is the option with the highest score in the relative preferences vector.
References	6, 8, 13, 15, 16, 18, 19

A3.7.3.3 <u>**Fuzzy Decision Theory**</u>

<table>
<tr><th>Method Name</th><th>Fuzzy Decision Theory</th></tr>
<tr><td>Method Summary</td><td>
Fuzzy Decision Theory is the result of the application of fuzzy set theory to decision theory. To understand how this works, it is first important to explain how classical set theory can be applied to decision theory.

The basis of classical (non-fuzzy) set theory is the set. A set is a category and set theory deals with manipulating these categories. A set has a very specific definition with no room for ambiguity. For example, to define the set of “fast ships” it is necessary to define a cut off speed, say 25 knots. All ships will then either belong in the set of fast ships (those faster than 25 knots) or outside the set (those slower than 25 knots). A membership function (represented by μ) describes the set mathematically:

$$\mu_A(x) = \begin{cases} 1 \text{ if } x \in A \\ 0 \text{ if } x \notin A \end{cases}$$


For a set of "fast ships" (A), a ship (x) has a membership value of 1 if it is a member of A (faster than 25 knots) and a membership value equal to 0 if it is not a member of A (slower than 25 knots). A graph of this function is shown.

For a ship to be a member of two sets A (fast ships) and B (long-range ships), then it must be a member of the intersection of A and B (denoted A∩B). The membership function in this case therefore becomes:

$$\mu_{A\cap B}(x) = \begin{cases} 1 \text{ if } x \in A \text{ and } x \in B \\ 0 \text{ if } x \notin A \text{ and/or } x \notin B \end{cases}$$

This function may be created arithmetically by selecting a suitable function, For intersections, there are several avaiiable which produce the desired result. The two simplest involve selecting the minimum membership value for each set, or by simply multiplying the membership functions for each set. This is written as

$$\mu_{A\cap B}(x) = \mathrm{Min}\ \{\mu_A(x), \mu_B(x)\}$$
or
$$\mu_{A\cap B}(x) = \mu_A(x) \times \mu_B(x)$$

If the sets are defined as the criteria (fast, long range), it is possible to determine whether a ship meets these criteria by examining the membership value for the intersection of the criteria. The membership value will be 1 if the ship meets all criteria and 0 if it does not meet all criteria.
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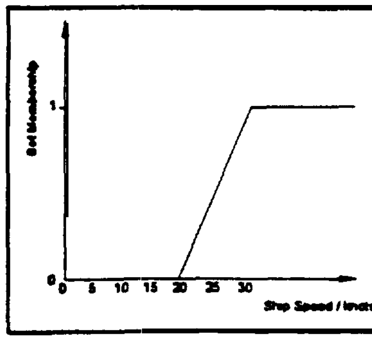
Method Summary (continued)

Fuzzy Set Theory extends the classical set theory by modifying the membership functions to include vagueness associated with descriptive words. For example, a 24 knots ship would be described as "Quite Fast", meaning that it should be somewhere in between "Fast" and "Not-Fast". Fuzzy set theory does this by allowing membership functions to have values between 0 and 1. The new membership function is shown.



Applying the same reasoning as with classical set theory, the membership function of a ship which satisfies all of the criteria can be determined by applying one of the intersection functions. The two examined here are selecting the minimum membership value for each of the criteria or multiplying each of the membership values together. Either method will produce a value for the ship which represents how well the ship satisfies th selection criteria. The ship with the highest membership value is therefore the one to be recommended.

Advantages

- The concept of fuzziness has been investigated extensively and has bee shown to be an excellent concept to use in everyday control systems. This is because humans, and nature in general, operate in a "fuzzy" world. In certain situations decision making can be also be fuzzy, particularly when concepts and preferences are vague. In these circumstances, fuzzy decision analysis may prove to be useful.

Disadvantages

- The main disadvantage with using fuzzy decision theory is the level of scepticism applied to this relatively new adaptation of fuzzy theory. Most observers are concerned about two central aspects of the theory.
- The first concern is with the interpretation of the membership functions. It is not clear bow the phrase "the membership of alternativ A in the set Good Decision is 0.61; the membership of alternative B in the same set is 0.49" should he interpreted. There seems to be no guarantee that selecting the option with the highest membership function is the right decision to make.
- The second area of concern is in the seemingly arbitrary choice of function to describe set intersections and unions. Although each function is logically correct for the classical set theory, there is some difficulty is justifying the same procedure for the fuzzy case.

Example

Three ship designs are Proposed as solutions to a problem and selection is to be made on three criteria; range, speed and endurance. The performance figures for each ship are shown in the table opposite.

	Range	Speed	Endurance
Ship 1	1800nm	25kts	25 days
Ship 2	2000nm	21kts	28 days
Ship 3	2300nm	23kts	24 days

Example (continued)

The first step in selecting the best decision is to determine the membership function for the sets "Long Range", "Fast" and "Long Endurance".

Membership function	Range (nm)	Speed (knots)	Endurance (days)
1.0	2500	40.0	32.0
0.9	2400	34.5	31.5
0.8	2300	28.5	31.0
0.7	2200	23.0	29.0
0.6	2100	17.3	26.5
0.5	2000	13.4	23.5
0.4	1900	10.5	20.0
0.3	1800	9.5	16.0
0.2	1700	8.5	11.5
0.1	1600	8.2	6.5
0.0	1500	8.0	1.0

This process was described in the method summary section and involved "smoothing" out the step membership function associated with classical set theory and introducing a certain amount of fuzziness to the descriptions of long range, fast and long endurance. The table above gives an example of typical membership functions. Notice that while the range function is linear, the speed and endurance parameters are not.

To solve for the best decision, it is useful to assign S_1, S_2 and S_3 to denote the three ships, and A, B and C to denote the three sets representing range, speed and endurance respectively. Summarising the performance figures for the three ships in set notation gives:

$\mu_A(S_1) = 0.30$ $\mu_B(S_1) = 0.73$ $\mu_C(S_1) = 0.55$
$\mu_A(S_2) = 0.50$ $\mu_B(S_2) = 0.67$ $\mu_C(S_3) = 0.68$
$\mu_A(S_3) = 0.80$ $\mu_B(S_3) = 0.70$ $\mu_C(S_3) = 0.52$

To determine the best option of the three available, it is necessary to establish the membership of each ship to the set "Long Range, Fast & Long Endurance". This set is defined as the intersection of the three individual sets A, B and C. The multiplication method (or other method if appropriate) is then used to establish the membership of each ship to the intersection set:

$$\mu_{A\cap B\cap C}(S_1) = \mu_A(S_1) \times \mu_B(S_1) \times \mu_C(S_1) = 0.30 \times 0.73 \times 0.55 = 0.12$$

$$\mu_{A\cap B\cap C}(S_2) = \mu_A(S_2) \times \mu_B(S_2) \times \mu_C(S_2) = 0.50 \times 0.67 \times 0.68 = 0.23$$

$$\mu_{A\cap B\cap C}(S_3) = \mu_A(S_3) \times \mu_B(S_3) \times \mu_C(S_3) = 0.80 \times 0.70 \times 0.52 = 0.29$$

Thus, ship 3 is the option recommended in this example.

References: 3, 5, 6, 16

A3.7.3.4 Cost Benefit Analyses

Method Name	Cost-Benefit Analysis
Method Summary	**Cost-Benefit Analysis (CBA)** has for a long time been the form of decision making most commonly used by governments and government agencies. There is a variety of reasons for its popularity, perhaps the most obvious being its apparent objectivity. Cost benefit analysis is based on economic theory and consequently attempts to reduce all parameters to monetary values. Every solution to the given problem has a cost which needs to be determine-d within a specified market environment. (Refer to Section A3.3 for more information on costing and costing methods particularly A3.3.4 investment appraisals). The costing exercise is usually relatively straight forward, although there is often some ambiguity as to where to place the bounds for the costing procedure. For example, modern naval theory demands that a fleet must have air superiority before it can perform minehunting operations. There is therefore the argument that the cost of buying and running a minehunter should include part of the cost of an aircraft carrier. The second, and more controversial element of CBA, is how to deal with the benefits. Generally, the aim is to establish a method whereby subjective judgements are eliminated and an objective method determined to convert benefits into monetary values. Sometimes this may be a straightforward task but more often the measures of benefit seem to be totally intangible to monetary value. If a suitable method can be found, then this (apparent) objectivity allows decision makers to distance themselves from the responsibility of expressing subjective values. Having established the monetary values for the costs and benefits, it simply remains to establish the "monetary value" for each option. Here, benefits are taken as positive values and costs as negative. Each option will be assigned a total monetary worth. An option whose benefits exceed costs will receive a favourable recommendation. An alternative measurement often used is benefit to cost ratio. This is generally used when there is more than one option being considered.
Advantages	• As has been mentioned, eost benefit analysis is the form of decision making traditionally favoured by governments. The reason for this is that the method seems to eliminate all traces of subjective values. This makes the justification for the decision made more impersonal, and, when dealing with other people's money (eg. the taxpayer), more politically acceptable.
Disadvantages	- The most obvious problem with this method is in the assumption that benefits can be freely converted into monetary values. There is still great controversy about this assumption, one that has still to be resolved. However, what is certain is that the majority of non-economists see the conversion of intangible attributes, such as risk and uncertainty or crew morale, into monetary values as highly dubious. • The method also assumes that money is the only valid criterion for making a selection. This may not always be the case.
References	1, 2, 3, 8, 10, 12, 16

A3.7.3.5 **Interactive Multi-Objective Programming**

Method Name	Interactive Multi-Objective Programming
Method Summary	Like most multi-criteria decision models, interactive **multi-objective** programming **(IMOP)** requires the decision maker to make a significant contribution in the data gathering stage. This is where his "subjective values" are collated. Most models then go on to use a variety of techniques to optimise these "values" in order to achieve an optimum decision. In general, the decision maker is not a part of the **optimisation** process. This **may** seem unusual since it is during the optimisation task that the actual decision is made. The MOP technique was specifically designed to put the decision maker **firmly** back into the whole of the decision making **process.** The technique is essentially an algorithm, or a series of steps that the decision maker is led through in order to reach his goal. The success of **IMOP** stems **from** its ease of use and complete intuitiveness. The decision maker is not asked to make estimates of value or utility against a variety of options, nor is he required to respond to a multitude of simple questions. Various algorithms for **IMOP** have been suggested, each with a varying level of complexity and subtlety. Each method, however, is based on the following simple procedure:- For a given problem, there are a number *(n)* of feasible, practical solutions $a_1, a_2, \ldots$ a,. It is not necessary for these alternative solutions to be defined before the selection procedure commences. The decision maker, however, needs to be aware of the range of possible solutions to the problem. In most other decision methods, the value or utility for the various solutions would be determined and the optimum solution selected. With **IMOP,** however, the decision maker is offered one trial solution, a_0. **The** decision maker must then determine an "improvement" a, such that he prefers a_1 to *a,*. This is again repeated, using interactive dialogue between various parties, each time arriving at a practical solution a_n which is preferred over *a,,*. **The** process is said to have converged when the decision maker feels that the solution a_n is satisfactory. It is important to notice that the decision maker is not **asked** any hypothetical questions as each decision is being made between two real alternatives. He is also being asked to choose between two complete solutions a, and a_{n-1}. There is no time spent on analyzirig the preferences of particular aspects of the solution; the decision is a holistic one. The method does assume, however, that the decisions beiig made are consistent. This unreliable assumption is the main draw back with the method.
Advantages	• **As** the reader will have **realised,** the interactive *multi-objective* **programming** technique is perhaps the simplest of decision making techniques. This stems from the fact that decisions are based on real, whole solutions and that the decision maker's value: system is assumed to be valid and no attempt made to quantity it (as in the case of utility, for example). • In addition, the method ensures that the final option chosen is acceptable to the decision maker since he has chosen that option over **another.**

Disadvantages	- The fundamental drawback with IMOP is that it assumes that the decision maker has to have an implicit unstated value system and makes consistent decisions based on that system. So, every time he makes a holistic preference of one option over another, it is vital that the decision is consistent with the previous and subsequent decisions. Unfortunately, experiment and experience has shown that people will always have a tendency to make inconsistent decisions. This is the reason why the theory of decision making was first studied. - To make matters worse, although theory relies on consistent decision making, the method does not provide the means to check whether this is the case or not. It is therefore possible that the decision maker is making totally arbitrary decisions and the method will provide no indication that this is so.
References	14, 16

A3.7.3.6 Consensus Decision Support Program

Method Name	**Consensus Decision Support Program (CDSP)**
Method Summary	CDSP is a method to measure and find consensus in a group who have already evaluated alternatives. Each member of the group ranks the alternatives, there beii no requirement to quantify by how much any alternative is preferred over any other. Ties are allowed. The programme calculates a rank correlation matrix and determines a coefficient of concordance among the group members.
Advantages	- Only rankings of alternatives or options are required. Each member may use any method to obtain this ranking. By requiring only a simple ranking of alternatives, possible inconsistencies caused by intransitive pair wise rankings are avoided.
Disadvantages	- With a small number of alternatives and a small number of members of the group, consensus may not be possible due to intransigence. The method is metric-free (ie. no distance between the rankings is required) and decision makers may require an estimate of 'how much' better various options are.
Example	see below
References	21

Example

Number of Players = 5
Number of Options = 8
Number for Majority = 3

Rank	1	2	3	4	5	6	7	8
Player								
I	7	1	4	5	6	2	3	8
II	5	3	7	4	1	6	2	8
III	1	S	3	2	6	7	4	8
IV	6	3	7	4	1	S	2	8
V	3	7	S	1	6	2	4	8

Matrix of Rank Correlation Between Players

1. I	1.00				
2. II	.36	1.00			
3. III	.14	.36	1.00		
4. IV	.29	.36	.14	1.00	
5. V	.29	.36	.43	.43	1.00

Consensus Test Statistic: 3.756 (from N [0,1])
Tail Area = .000
Comment: Statistically significant level of consensus exists

Solution 5 3 7 1 6 4 2 8

Option 5 is thus ranked as the first with option 3 as the second.

A 3 . 7 . 3 . 7 **PREFER**

Method Name	PREFER
Method Summary	PREFER is a method for ranking and grouping alternatives in a selection process subject to various criteria. The formulation is based on order-statistics to construct a reference frame against which a given set of alternatives can be measured. The objects are then classified into one or more groups in which all objects in a group are equivalent in utility at a given level of significance.
Advantages	- Decision makers are given a number of groups each of which contains one or more alternatives. The DM is usually given a choice in the most preferred option, thereby allowing for non-quantified judgements in the final selection process.
Disadvantages	- The method is quantitatively extensive and requires an experienced facilitator. Each criteria requires the same scoring procedure, typically 0 to 100.
Example	Nine companies have submitted proposals for a 13kW diesel generator. Their proposals are evaluated against fifteen selection criteria, each criteria being scored from 0 to 100. Weights are associated with each criteria. PREFER determines a utility vector for each company proposal and then determines, at a specific level of significance α which proposals are essentially equivalent. With $\alpha = 0.20$, four equivalence classes emerge. The DM then selects a proposal from the highest equivalence class.
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A 3 . 7 . 4 References

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ANNEX 4.0 - APPLICATION EXAMPLES

The purpose of this annex is to present practical examples of COEA processes. These examples are not intended to be definitive but to illustrate applications of some of the methods detailed in Annex 3.0.

Two examples are presented

- Surface fleet mix effectiveness study
- Rapid route survey craft assessment

The first example is not directly concerned with hull type selection for a particular role but with high level decisions on future fleet make up, which could include different craft types. The second example describes a theoretical study performed as part of the assessment of alternative rapid route surveillance designs produced under the aegis of NATO's SWG/6 Advanced Naval Craft studies.

The methods used in each study are summarised in the following table

Methods	Study	
	Surface Fleet Mix Effectiveness	Rapid Route Survey Craft Assessment
Requirements Analysis	- Prior analysis - Subjective judgement	-
Operational Effectiveness	- Analytic solutions - Simulations - Subjective judgement	- Simulations - Subjective judgement
Costing	- Top down, parametric - Life cycle costing	- Top down, parametric - Life cycle costing
Timescales	-	-
Uncertainty	- Sensitivity analysis	- Sensitivity analysis
Risk	-	-
Multi Criteria Decision Making	- Analytic hierarchy process - Consensus decision support program	- Multi attribute value theory

A4.1 SURFACE FLEET MIX EFFECTIVENESS STUDY

This example details a high level study into overall naval fleet composition necessary to meet a defined set of requirements. The procedure followed and methods adopted are applicable to any similar problem.

A4.1.1 Scenario

The study was required to determine the most cost effective choice of new ships to augment an existing fleet. The goal beii to produce an optimum fleet mix with the capability to meet assigned naval takings.

Prior to this study more detailed modelling investigations had already been performed on the performance of particular vessels in specific scenarios. These results had to be reviewed in the context of the overall fleet make up. Si objective modelling was not possible on such a wide ranging problem the conduct of the study depended heavily on the experience and judgement of a panel of experts. Therefore methods were needed that would capitalise on this knowledge and enable it to he captured and analysed in a traceable and auditable fashion. Accordingly two Multi Criteria Decision Making methods were selected, the Analytic Hierarchy Process (section A3.7.3.2) and an application of the Consensus Decision Support Program (section A3.7.3.6).

A4.1.2 Study

The study can be considered under the four phases of a general COEA (section 2.3).

A4.1.2.1 Determination of Operational Requirements

In order to arrive at a set of criteria against which the performance of candidate fleet mixes could be assessed a requirements development process was needed. Input to the process was provided from the high level national and international policy objectives. The required outputs were the low level attributes of particular vessels. A means of relating the input objectives with the desired output <attributes was needed. This was achieved by a two stage process combining both top-down and bottom-up approaches.

- Top-Down
  'he first, top down, stage was to identify the tasks or missions needed to fulfil the overall objectives or goal.

- Bottom-Up
  The second, bottom up. stage was to identify the attributes of the candidate naval forces and then to map these attributes onto the tasks identified in the first stage.

Considering first the identification of tasks to be performed, the National Objectives cover two domains of interest or tasks defined as follows

- **Surveillance and Sovereignty Enforcement**
  This would be essentially a detect and deter role designed to protect the country's national interest in her home waters during peace time. The role requires a surveillance capability and the means to intercept any intruders and enforce national and international laws in support of civil authorities. Any military threats to the vessel would be considered to be of a low level.

- **Support to other Government Departments**
  These activities would cover several roles
  - Fisheries patrol/protection
  - Drug interdiction
  - Counter illegal immigration
  - Search and rescue
  - Environmental monitoring

The International Objectives were broken down in a similar fashion as follows

- **Conflict**
  High intensity conflict would require the vessels to operate under an intense multi threat environment. In addition there **are** some environments where a low or medium threat level would enable less capable vessels to operate satisfactorily.

- **Peacekeeping/Enforcement Operations**
  These operations would generally be performed together with allied forces under no more than low intensity threat levels. The vessels could be required to operate in conjunction with land forces ashore in littoral environments.

- **Afloat Logistics Support**
  This task definition was made up of three elements
  - **Sealift**
  - Support to shore forces
  - Replenishment at sea of naval forces

The second stage of the requirements definition process was to identify the attributes of candidate fleets that would be appropriate to the tasks identified above. Each attribute may be relevant to one or more tasks, however it was important that each was independent of the others. This meant that each definition described features not covered by any other. The ten attributes that were identified were defined as

- **Surveillance Capability**
  This covers the ability to detect air, surface and sub surface contacts. It also includes Electronic Surveillance Measures.

- **Engagement Capability**
  The ability to engage or defend against an enemy.

- **Data Fusion**
  Describes the functions of Command, Control and Communications together with the **facilities** to combine intelligence and data from several sources and present it in a **useable** format to **the command** team.

- **Cruise Speed**
  Average most economical transit speed.

- **Maximum Speed**
  Average maximum speed.

- **Endurance**
  The ability to remain at sea without replenishment. A mix of 90% cruise speed and 10% maximum speed was assumed, together with appropriate stores usage, in order to calculate an average endurance figure.

- **Survivability**
  Describes the ability of ships to avoid attack, susceptibility, and to withstand damage when attacked, vulnerability. The attribute therefore covers signatures and damage control measures.

- **RAS Capability**
  The ability of the fleet to supply itself with fuel and stores whilst at sea.

- **Sealift Capacity**
  Covers the requirement to carry vehicles, equipment, containers and personnel and then to discharge them at their destination.

- **Organic Air Capability**
  The ability of the fleet to operate and maintain its own shipborne aircraft, specifically helicopters and unmanned airborne vehicles.

A4.1.2.2 Definition of Systems

The baseline for the study was the existing fleet composition. All the other options to be considered were made up of the baseline with additional units of various types and in various combinations. The kinds of vessels to be considered were

- **General Purpose Frigate**
- **Surface Effect Ship** (SES)
- **Low Cost General Purpose Frigate**
- **General Purpose Frigate Variant**
- **Offshore Patrol Vessel**
- **Multi Role Support Vessel**
- **Auxiliary Replenishment Vessel**
- **Roll On/Roll Off (RO/RO) Vessel**

Initially 20 combinations, comprising the base line fleet and the baseline plus various additional units, were selected as follows

Option	Ship Types							
	General Purpose Frigate	Surface Effect Ship	Low Cost General Purpose Frigate	General Purpose Frigate Variant	Offshore Patrol Vessel	Multi Role Support Vessel	Aux. Replenish Vessel	Roll On Roll Off Vessel
A Baseline								
B		6						
C			6					
D				6				
E					6			
F						6		
G						4		
H						2		
							2	
								2
K		4						
			4			2		
M								
					4	2		
O		2				4		
P			2			4		
Q				2		4		
R					2	4		
S	2							
T						2		

Note that in option T the base line was modified by removing two of the original vessels.

A4.1.2.3 Analysis of Costs and Benefits

Various tools and methods were used to calculate, and where necessary estimate, the costs and benefits of the options.

A4.1.2.3.1 Analysis of Costs

The Life Cycle Costs were divided into Total Acquisition Costs and Annual Operating and Support Costs. The former being split between Customer Procurement Project Costs and Sailaway Costs. These were calculated on the following basis

- **Life cycle costs**
  - **Total acquisition costs**
    - Customer project costs
      Calculated on the basis of a fixed percentage of the sailaway costs. Past experience was used to estimate a figure of 40%.
    - Sailaway costs
      Estimated by using simple Cost Estimating Relationships (CERs) based on a design work breakdown structure. The structure comprised the following groups
      - Hull structure
      - Propulsion system
      - Electrical power generating plant
      - Command and surveillance systems
      - Auxiliary systems
      - Outfit and furnishings
      - Armaments
      - Design and build margin

      Costs for the above groups were based on CERs related to the weight of material in each group and past experience of similar vessels. Two additional groups were added to the above work breakdown
      - Integration and engineering
      - Construction services

      Costs for these two groups were obtained by using CERs based on both weight and factors relating to design complexity.
      In all cases the CERs were determined from past data modified to take account of any differences in construction standards as appropriate. For example some vessel options could be built to commercial rather than military standards and so a factor was used to reflect the lower expected costs after initial estimation using past military ship data.
  - **Operating and support costs**
    These were generated using a generic ship operating cost model which calculated costs based on raw cost data for particular items and an assumed operating profile for the vessel
    - Fuel
      Costs based on a specified number of days at sea for each vessel together with percentage time spent at each speed and anticipated helicopter usage.
    - Personnel
      Based on average pay levels for officers, NCOs etc. and days at sea.
    - Operation and maintenance
      Made up of costs of weapon rounds and assumed usage, maintenance costs based on initial ship cost and size together with the costs of any additional special facilities **specific to the vessel.**

The costs calculated for each option were as follows

Option	% Increase over baseline
A	0
B	29
C	30
D	34
E	29
F	33
G	22
H	11
I	11
J	4
K	30
L	31
M	33
N	30
O	31
P	32
Q	33
R	31
S	16
T	11

A4.1.2.3.2 Analysis of Benefits

Three methods were used to estimate the benefits that could be obtained from the fleet mixes. These included both quantitive analysis and qualitative assessments.

Quantitive Analysis was performed using a Scheduling Model. This provided an optimum peacetime sea operations schedule for a given fleet mix and a defined set of missions. Constraints such as overall fuel budgets, adequate maintenance and crew rest periods and ship allocation to specific missions were included. The outputs were the number of fixed duration missions and ship days away from home port and these became the measures of effectiveness for any particular fleet mix. The program also calculated the actual fuel used and any other associated costs.

The missions used as input to the model were as follows

Mission	Duration days
Surveillance and Sovereignty Enforcement	14
Support to Other Government Departments	14
Peacekeeping and Enforcement Operations	90
Sealift and Humanitarian Aid	90

An example output from the analysis for a constrained overall fuel budget is as follows

Option	Away days	Surveillance & Sovereignty Enforcement	Support to Government Departments	Peacekeeping/ Enforcement	Sealift/ Humanitarian Aid
A	2771	2	8	3	1
B					
C	2771	2	8	3	1
D	2841	4	11	3	1
E	2771	2	8	3	1
F	3265	10	16	4	3
G	3113	11	17	3	2
H	2981	9	16	3	1
I	3063	6	12	4	2
J	3105	7	14	3	3
K					
L	2771	2	8	3	1
M	2841	4	11	3	1
O					
P	2897	6	13	3	1
Q	2925	6	15	3	1
R	2939	7	15	3	1
S	2771	2	8	3	1
T					
A+	2855	5	11	3	1
Requested missions		14	20	7	3

By performing a variety of runs this analysis provided information on the vessel utilisation potential for the peacetime missions and the associated costs for each of the different fleet options. An additional option A+ was included in the analysis. This represented the current fleet with an additional fuel allocation made available.

Some general conclusions were drawn from this analysis

- The SES was dropped from the analysis as it had a high fuel consumption but similar capability to other classes.
- The most cost effective way to increase fleet deployment is to increase the fuel budget and maximise usage of current vessels.
- More support vessels is the most effective way to increase fleet activity.
- Fleet effectiveness is increased by more fuel or reassigning missions to ships with lower fuel consumption.

More detailed comparisons between particular ship types were also made such as

- Roll on roll off vessels provide the cheapest increase in days away but are inadequate to provide afloat logistic support.
- Multi role support vessels are more cost effective than auxiliary replenishment vessels except when fuel is limited.
- There is no advantage in going from 4 multi role support vessels; to 6.
- Two general purpose frigates are better than 6 multi role support vessels provided that the fuel budget is available.
- Adding 2 support vessels increases the Surveillance/Sovereignty Enforcement, Support to Other Government Departments and Sealift/Humanitarian Aid missions.

This analysis did not provide any assessment of the suitability of each vessel to perform the allocated missions. The missions had to be assigned to vessel types in the input data.

In order to assess the suitability of vessels for particular roles and to provide an overall assessment of fleet mix, **Qualitative Analyses** were performed using a team of experienced assessors. Two methods were adopted in order to provide a framework for the assessments and ensure that any method induced bias was detected and eliminated.

The first approach **used the** Analytic **Hierarchy Process (AHP).** The process was implemented in several **stages.**

- **Ranking of tasks**
  This stage entailed assessing the relative importance of the five tasks and the likelihood of their occurrence. This was provided by the subjective judgement of the assessment team.

Mission	Importance	Likelihood
Surveillance and Sovereignty Enforcement	0.183	0.461
Support to Other Government Departments	0.049	0.219
Conflict	0.519	0.040
Peacekeeping and Enforcement Operations	0.102	0.151
Afloat Logistic Support	0.147	0.128

- **Rate attributes against national tasks**
  In this stage the national tasks of Surveillance and Sovereignty Enforcement and Support to Other Government Departments were assessed. The assessment team decided that six attributes were relevant to the missions and that they rated differently to each one.

Attribute	Surveillance and Sovereignty Enforcement	Support to Other Government Departments
Surveillance Capability	0.227	0.243
Data Fusion	0.305	0.293
Cruise Speed	0.072	0.060
Maximum Speed	0.064	0.080
Endurance	0.183	0.134
Organic Air Capability	0.149	0.190

- **Assess ship types against attributes**
  The assessment team compared the candidate vessel's capabilities against the required **attributes.** The effect of **different** vessel **types was illustrated** by fleet enhancement options A, B, C, D, E and G, representing the baseline fleet and the fleet with additions of single vessel types. The weights derived from the **assessments are as shown**

Attributes	A	B	C	D	E	G
Surveillance	0.058	0.168	0.161	0.267	0.281	0.066
Data Fusion	0.065	0.106	0.236	0.236	0.236	0.121
Cruise Speed	0.162	0.100	0.183	0.162	0.223	0.170
Endurance	0.149	0.317	0.139	0.139	0.139	0.118
Maximum Speed	0.146	0.153	0.153	0.153	0.153	0.242
Organic Air Cap.	0.042	0.048	0.158	0.158	0.079	0.514

The resulting overall AHP model structure is shown in figure A4.1.1.

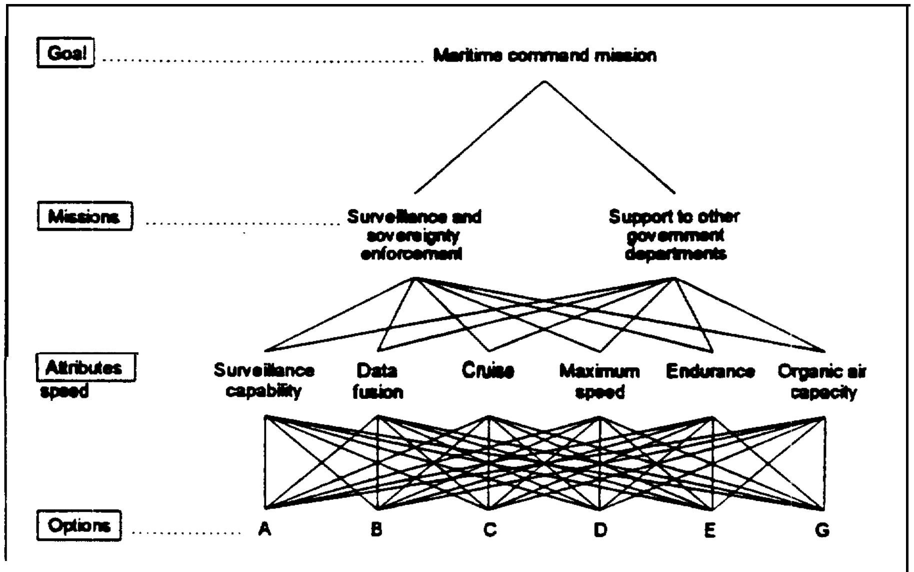

Figure A4.1.1
AHP Model for **National Missions**

Evaluating the model provided the following relationship for each fleet mix against the overall goal

Measures	A	B	C	D	E	G
Importance	0.086	0.133	0.182	0.205	0.200	0.194
Occurrence	0.086	0.133	0.182	0.205	0.200	0.195

- **Assess initial results**

  At this stage the results obtained were examined and as a result two vessel types, the SES and the Low Cost General Purpose Frigate (**B &** C) were dropped. It was also evident that the **Multi** Role Support Vessel was showing advantages and so the following fleet options were taken forward to the next stage, A, D, E, G, H, I, J, M, S and T.

- **Repeat assessments for National and International tasks together**

  During this stage the remaining three missions, Conflict, Peacekeeping and Enforcement Operations and Moat Logistic Support were added **to** the national tasks and all five **analysed. Now all ten** ship attributes identified during the determination of the operational requirements were considered relevant. Finally the ten remaining fleet mixes, were assessed against the attributes. The steps in the analysis were thus the same as for the National tasks and the final results were as follows

Measures	A	D	E	G	H	I	J	M	S	T
Importance	0.061	0.137	0.135	0.117	0.071	0.085	0.046	0.130	0.137	0.082
Occurrence	0.055	0.143	0.138	0.124	0.072	0.081	0.048	0.137	0.117	0.084

Throughout the AHP analysis careful notes were taken of the differing opinions of team members and extensive sensitivity analyses carried out in order to gauge the effect of the differences on the **results. These** studies showed that the largest possible change in weight for the most contentious assessment was about 8%. This reflected a high degree of agreement among the team and resulted in a robust result.

The second qualitative assessment approach **to be used was the Consensus Decision Support Programme (CDSP).** This process was implemented in stages as follows

- **Individual Task - Fleet Assessment**

  During this stage each member of the team independently ranked each fleet mix against each of the five tasks. The options were given a rank ordering with tied options being allowed. No scale *or* relative magnitude was ascribed to the rank order. The options considered were all the twelve mixes used in the AHP together with option N which included Offshore Patrol and Multi Role Support Vessels.

  The results of the individual task assessments were as follows

Option	Surveillance & Sovereignty Enforcement	Support to Government Departments	Conflict	Peacekeeping/ Enforcement	Afloat Logistic Support
A	12=	13	12=	13	13
B	9	8	6=	12	12
C	5	5	6=	10	11
D	3	3	2	3=	8==
E	4	4	3	5	8==
G	7	7	8=	6	1
H	11	10	11	8	6
I	10	11	10	9	3
J	12=	12	12=	11	7
M	1	1	4	1	4
N	2	2	5	2	5
S	6	6	1	3=	8==
T	8	9	8=	7	2

The individual assessments were then combined into a single ranking in two ways

- **Tasks equally weighted**

  Each of the five tasks was assigned an equal weighting.

- **Tasks Nationally weighted**

  In order to reflect the higher likelihood of the National tasks occurring a two stage calculation was performed. In the first stage the three international tasks, Conflict, Peacekeeping and Enforcement Operations and Afloat Logistic Support were combined into a single ranking. During the second stage, the resulting International ranking was weighted equally with the two National tasks, Surveillance and Sovereignty Enforcement and Support to Other Government Departments to produce an overall ranking, effectively with a National weighting.

- **Overall Goal - Fleet Assessment**
  In this case the assessment team were asked to rank the fleet mixes against the overall goal **defined** as a **combination** of all five tasks. This ranking thus incorporated the team's subjective **weightings** for the relative importance and likelihood of each task. The results of the various combinations of task rankings and overall goal ranking were as follows

Option	Equally Weighted	National Tasks Weighted	Overall Subjective Ranking
A	13	13	13
B	9	9	11
C	6	5	10
D	3=	3	7==
E	5	4	7==
G	7	7	3=
H	11	11	5
I	10	10	6
J	12	12	12
M	1	1	1
N	2	2	2
S	3=	6	7==
T	8	8	3=

An important aspect of the process was to establish the reasoning behind the **judgements.** In order to facilitate this the team members were asked to rank fleet attributes against each task. The attributes identified were those used in the AHP analysis but with the additions shown below.

Attribute	Surveillance & Sovereignty Enforcement	Support to Government Departments	Conflict	Peacekeeping/ Enforcement	Afloat Logistics Support	Overall Goal
Surveillance Capability	1	1=	3	3		3=
Engagement Capability	5=		2	2		2
Data Fusion	2	1=	1	1		1
Cruise Speed						
Maximum Speed						
Endurance	3=	3==		4		
Survivability			4			6==
RAS Capability					1	6==
Sealift Capacity					2	6==
Organic Air Capability	3=	3==		5	4	5
Seakeeping						
N° of Capable Ships	5=	3==	5		5	
Joint Operations					3	3=

During the associated discussions the team identified an additional attribute, Flexibility and Balance, as being important. Although this was not analysed explicitly it played an important part in the subjective judgements.

The results of the Consensus Decision Support Programme study can be summarised as follows

- For the two National tasks and the Peacekeeping and Enforcement tasks options M and N are ranked first and second. This is also reflected in the overall assessment.

- The two National task options have almost the same rankings.

- Options S, D and E rank highest for the Conflict task. Options with combat ships score higher than those with support vessels.

- The four tasks with a combat element were ranked similarly
  - Multi role support and combat mixes (M and N) and combat only mixes (C, D, E, and S).
  - Strong support mixes (G and T).
  - Weaker support mixes (I, H and J).
  - Baseline (A).

- The Afloat Logistic Support task was ranked
  - Strong support mixes (G, T and I).
  - Multi role support and combat mixes (M and N).
  - Weaker support mixes (H and J).
  - Combat mixes (D, E, S, C and B).
  - Baseline (A).

- The overall Goal rankings were
  - Multi role support and combat mixes (M and N).
  - Strong support mixes (G and T).
  - Weak support mixes (H and I).
  - Combat mixes (D, E, S, C and B).
  - Roll on roll off mix (J).
  - Baseline (A).

A4.1.2.4 Selection of Most Cost Effective System Concept

The results of the cost and benefit assessments were displayed on cost benefit plots. The data was presented at many intermediate levels in order to aid understanding of the factors present. Example plots produced by the AHP analysis for the overall cost effectiveness of ten fleet mixes with respect to the Overall Goal is shown in figures A4.1.2 and A4.1.3.

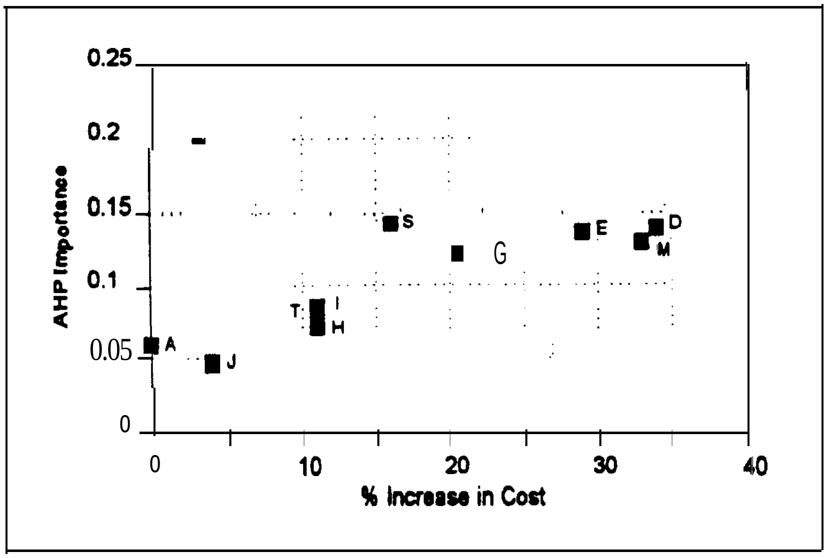

Figure A4.1.2
AHP Importance Cost Benefit Plot

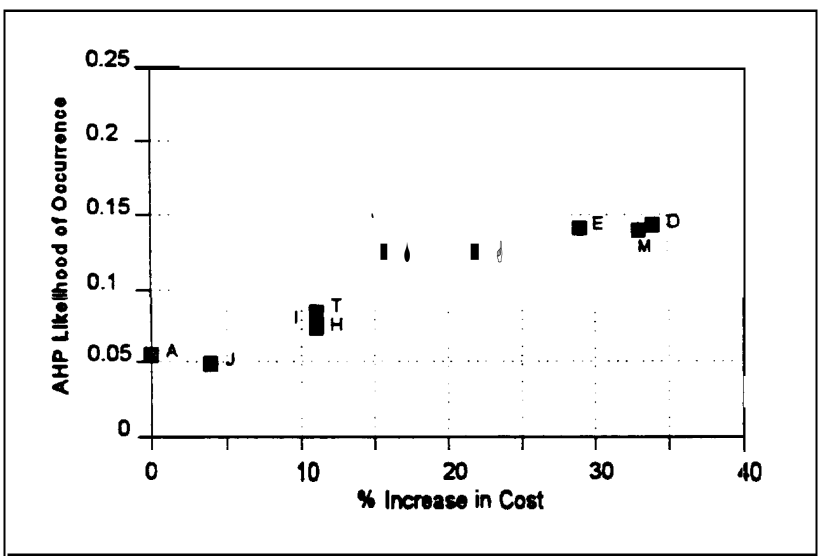

Figure A4.1.3
AHP Likelihood Cost Benefit Plot

These plots show a close relationship between cost and benefit but closer examination indicated the following

- Given an incremental increase in costs, the first priority is for additional support ships with a multi role capability **(T,** I, **H).**

- A single role vessel such as the roll on roll off is not cost effective. It does not add to the tasks and indeed in some scenarios it becomes a liability as it can not defend itself(J).

- The most cost effective addition is two general purpose frigates. This is because of the importance placed on the Conflict task This option is more costly than the addition of support ships (S).

Similar plots can be produced for the results of the CDSP analysis. However as the rankings do not represent absolute differences between options care must be taken in their interpretation. An example plot for the nationally weighted rankings against percentage increase in cost over the baseline is shown in figure A4.1.4.

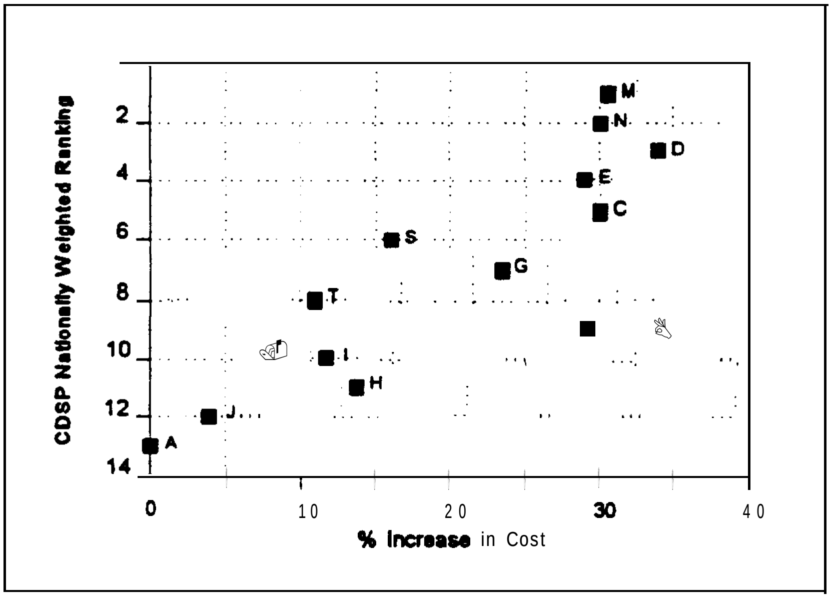

Figure A4.1.4
CDSP Ranking Cost Plot

In making recommendations it was important to consider the different perspectives provided by the different methods of analysis. The overall conclusions can be summarised as

- **Task priority**
  The task importance order of Conflict, Surveillance and Sovereignty Enforcement, Support to Government Departments, Peacekeeping and Enforcement and Afloat Logistic Support has a major bearing on fleet selection.

- **Task occurrence**
  The Surveillance and Sovereignty Enforcement and Support to Government Departments tasks were rated to be more likely than the others. This factor balances their relative importance **and so fleet mixes should reflect this.**

- **Quantity**
  In general the most effective fleet mixes were those with the most hulls coupled with increased support. The exception was the addition of two general purpose frigates. More hulls increases flexibility.

- Desirable attributes

The following was noted

- Speed was not important.
- Data Fusion was rated most important for all tasks **except** Afloat Logistic support.
- Organic Air Capability was important **but is provided by the** current fleet.
- **Sealift** and RAS Capability are only important to Afloat Logistic Support.
- Ships that have low survivability and can not defend themselves are a liability.

As a result of these observations it was concluded that the priorities for fleet enhancement would be to

- Firstly improve Afloat Logistics Support by acquiring Multi Role Support Vessels fitted to conduct Surveillance and Sovereignty Enforcement tasks and replace existing Auxiliary Replenishment vessels with a more modem capable type.

- Secondly to acquire additional combat capable vessels such as General Purpose Frigates or variants.

It is important to note that the study generated a range of information designed to inform and support the decision making process. No one table of data or figure **defined** the solution in isolation but the information generated ensured that all factors were considered and a balanced and justifiable conclusion reached.

A 4 . 1 . 3 References

1. "Surface Fleet Mix Effectiveness Study (SFMES) : Final Report"
Director Naval Requirements, Department of National Defence, Ottawa, Canada, November 1993

A4.2 RAPID ROUTE SURVEY CRAFT ASSESSMENT

This example describes an assessment of various designs produced against a requirement for a rapid route surveillance mine counter measures craft. Although the primary role of the craft was defined it was realised that in practice the vessels would be used for a variety of roles and so alternative missions were also postulated and evaluated.

A4.2.1 Scenario

Prior to tbis study several alternative designs had been produced against a set of mission requirements for a rapid route surveillance mission. The designs were

- **Surface Effect Ship (SES)**
- **Monohull**
  A base design was generated together with two variants, a longer vessel optimised for seakeeping and a small low cost vessel.
- **Small Waterplane Area Twin Hull** (SWATH)
- **Air Cushion Vehicle (ACV)**

The designs had already been analysed technically and as a result of this the SES and Monohulls were taken forward for further analysis. The ACV could not meet the main mission requirement while the SWATH design had been insufficiently defined for comprehensive analysis.

The cost and mission effectiveness study was required to determine the most cost effective choice of hull type for the defined role. Accordingly the study concentrated on analysis of the mission performance of the SES and the three monohull variants.

A4.2.2 Study

The study was divided into the four stages of a COEA as follows

A4.2.2.1 Determination of Operational Requirements

The original requirements were for a rapid route surveillance mission in support of mine countermeasures operations. This mission called for the following performance

- **Range**
  Transit 250 nm to and 250 nm from mission area.
- **Speed**
  Transit speed in accordance with craft capabilities and weather conditions.
- **Endurance**
  A three to seven day mission was specified.
- **Payload Operation**
  While on station the craft was to tow a side scan sonar at **10** knots.

These requirements were very basic and in order to compare the real operational performance of the craft two specific missions were defined. Both covered the same distances but one was centred on the Western Approaches to the English Channel while the other was performed in the North Channel and Clyde area. The mission distances were as follows

- **Transit**
  250 nm at highest possible speed to operational port area.
- **operation**
  Three passes at 10 knots along a 200 nm channel giving a total survey run length of 600 nm.
- **Return**
  Return to operational port along searched channel at highest possible speed.

A Measure of Effectiveness was defined as follows

- **Coverage Rate** = Survey Distance / Mean Mission Time

Since the craft would inevitably also be used for other roles additional representative missions were defined

- **Anti Terrorist Coastal Patrol**
  This mission entailed patrolling along the coast around the Bay of Biscay searching for suspicious vessels offloading stores or personnel. It was assumed that such vessels would rely on secrecy to perform tbeii operations and so would be normal trading vessels with no abiity to flee once detected. Two forms of mission were to be examined, in the first the patrol vessel would rely on its on board radars with a 15 nm horizon to detect targets while in the second it would respond to targets detected by either a shore based radar chain or an airborne radar system. Effectively the latter option gave a 500 nm radar horizon. In both cases the measure of effectiveness was taken as being the Percentage of targets occurring that are successfully engaged.
- **Fisheries Protection**
  This mission involved patrolling an area checking for illegal fishing activities. This would necessitate detecting and pursuing a suspicious vessel, intercepting it and boarding it for inspection. It was assumed that such a vessel would attempt to flee once it detected the patrol craft. The mission area was defined as a box to be patrolled by means of several tracks totalling 450 nm in length. The craft could use either their own sensors or he cued by airborne surveillance. In addition two further options were considered. In the first a higher patrol speed, covering the tracks more often in the same time, was used, if available, while in the second the craft were considered to approach the target stealthily thus delaying the point at which the target attempted to flee. Both these latter mission options were performed using the extended offboard surveillance. The measure of effectiveness was defined as being Percentage of targets occurring that are successfully engaged.

In addition to tbe three primary roles identified above two additional secondary missions were identified

- **Flag Waving**
  This involved visits to foreign ports, holding receptions and entertaining dignitaries. A vessel's effectiveness could not be defined in a quantitive manner but would be affected by such parameters as available reception areas and overall image, both directly related to the vessel's size. Effectiveness would also depend upon the number of accessible ports, which was considered to be inversely related to sire.

- **Leasing**
  The vessels could also be leased to other government depanments or even private agencies for such roles as data gathering, surveying or trials purposes. Their effectiveness would be proportional to their available space and operational envelope, ie. speed and seakeeping.

A4.2.2.2 Definition of Systems

Four craft were investigated in the operational analyses and costing exercises

- **Surface Effect Ship**
  This was a large craft of 58 m LOA and 650 tonnes displacement. A top speed of 55 knots was achievable. Low speed towing was performed off cushion.
- **Baseline monohull**
  This was a 55 m LWL vessel of 517 tonnes displacement with a maximum speed of 15.5 knots.
- Seakeeping **Monohull**
  This was a variant of the base design stretched to 70 m LWL on a displacement of 1072 tonnes. The same maximum speed was retained. The effect of the increased length was to increase tbe limiting wave heights at which speed reduction was necessary by 20% over those for the baseline monohull.
- Low Cost **Monohull**
  This was a 40 m LWL vessel with a 200 tonne displacement and a 15.5 knot maximum speed. The effect of the decreased length was to decrease the limiting wave heights at which speed reduction was necessary by 20% below those for the baseline monohull.

Each craft was designed to accept the same operational payload comprising a towed side scan sonar, surveillance radar equipment and a small calibre gun. All the craft were assumed to have the same effective radar horizon for the purposes of this study.

A4.2.2.3 Analysis of Costs and Benefits

Costing and operational modelling studies were performed for each vessel with tlhe following results.

A4.2.2.3.1 Analysis of Costs

The costs were built up using a spreadsheet and covered a **20** year operational life for the vessels. Cost estimating relationships based on past experience and data were used together with known infrastructure and typical spares and support costings. Fuel costs were derived from assumed mission profiles and usage rates. In order to provide a base for comparison the costs were discounted to the project start date. The high level cost breakdowns that resulted were

Cost £M	Surface Effect Ship	Monohull Baseline 55 m	Monohull Seakeeping 70 m	Monohull Low Cost 40 m
First Of Class	30.3	23.4	36.2	11.3
Unit Production	28.0	21.7	33.6	10.5
Support	158.0	105.0	162.0	50.0
Personnel	51.0	57.0	61.0	54.0
Fuel	13.8	1.43	2.22	1.03

A4.2.2.3.2 Analysis of **Benefits**

Mission benefits were evaluated using a discrete event based simulation model (section A3.2.5.2). This model was designed to analyse the platform performance during a mission with particular emphasis on its interaction with the environment. In order to achieve this the model used recorded sea state time history data for a particular area. In this way time dependent effects could be accurately predicted. The model used the following data as input

- **Vessel capability**
  - Operating speeds and fuel consumption rates
  - Fuel and stores holdings
  - Operating modes
  - Seakeeping and limiting speeds
  - Additional vehicles such as helicopters or rigid inflatable boats
  - High level sensor and weapon performance
  - Equipment reliability rates and reversionary modes
- **Missions**
  - Planned tracks, speeds and operating modes
  - Intercept and engagement profiles
- Targets
  - Rate of occurrence
  - Speeds
  - Sensor and weapon capabilities
  - Response profiles, attack or evade etc.

The actual results achieved in any particular simulation run depended upon

- **Programmed events**
  - Planned mission profile
  - Environment, defined by recorded sea state time history data
- **Random events**
  - Equipment failures and repairs
  - Contact occurrence
  - Engagement results

Accordingly all runs were repeated several hundred times and the resulting converged average results used. The calculated measures of effectiveness for each mission and each craft were as follows

Measure of Effectiveness	Surface Effect Ship	Monohull Baseline 55m	Monohull Seakeeping 70m	Monohull Low Cost 40m
Route Survey	Coverage rate (Nm/Hr)			
Western Approaches	8.44	6.26	6.44	6.02
North Channel	8.67	6.53	6.63	6.39
Anti Terrorist	Percentage contacts engaged (%)			
Shipborne Sensor	38.9	37.7	38.2	37.5
Airborne Sensor	80.0	49.9	50.1	49.3
Fishery Protection	Percentage contacts engaged (%)			
Shipborne Sensor	10.7	8.1	9.1	7.2
Airborne Sensor	70.9	30.5	33.4	28.2
High Speed Patrol	18.5	8.1	9.1	7.2
Stealth Approach	66.9	9.5	10.4	8.7

During the simulation runs parameters were varied in order to establish the sensitivity of the results to particular input data assumptions. Parameters investigated were

- **Contact density**
  'Ibis was set to be low (averaging 1 per 24 hour period) in order to prevent simultaneous target occurrences affecting the success rate. Varying the density did not affect the results thus validating the initial assumption.

- **Pursuit distance hits**
  This parameter limits the time spent pursuing a target vessel if it attempts to evade. It was set at 4 hours and this was found to have no effect when the vessel was using its own sensors. It was significant however when offboard sensors were used as the intercept distances could be much longer.

- **Engagement environment limit**
  An engagement was considered to consist of a boarding operation conducted using the ship's boat. This would be weather limited and as expected this was found to be a dominant factor in determining the absolute figures for the results. The same value was used for all the vessels in order to focus the analysis on other aspects of the vessel's relative performance.

For the two secondary missions a comparative assessment was made by considering the attributes of the vessels relevant to the missions and marking each attribute subjectively on a scale of 0 to 100. In this case 0 represented the worst option and 100 the best.

Measure of Effectiveness	Surface Effect Ship	Monohull Baseline 55m	Monohull Seakeeping 70m	Monohull Low Cost 40m
Flag Waving	Subjective mark			
Size	42	31	100	0
Image	100	25	50	0
No. of Ports	0	82	50	100
Leasing	Subjective Mark			
Suitability	100	60	80	0

Some general observations resulted from the operational modelling studies

- **Transit speed**
  This is significant for the rapid route surveillance mission where it is important to obtain the results quickly. The SES with its high speed capability performs best in this role. However this is at the expense of much higher fuel costs. The extra seakeeping capability of the longer monohull has more effect in the more open Western Approaches environment but even here it only shows an average 7% improvement over the shorter Ship.

- **Surveillance range**
  When limited to ship's sensors there is very little difference between the four vessels. However increasing the surveillance range by using offboard sensors has two effects
  - The performance of all the vessels is improved
  - Ship speed becomes a factor. The SES with its higher maximum speed performs far better than the monohulls. This is because it is able to reach the target vessels before they have left the area.

- **Patrol speed**
  Covering the same area three times is an advantage for tbe SES in that this almost doubles its success rate (assuming ship borne sensors). However this causes an almost 14 fold increase in fuel usage.

In general the SES is shown to have potential performance advantages under some circumstances due to its far higher top speed capability. This is achieved with much higher fuel usage.

A4.2.2.4 Selection of Most Cost Effective System Concept

In order to combine the various measures of cost and benefit Multi Attribute Value Theory (MAVT) was used. The process was implemented in several stages

- **Establish model structure**
  The various costs and benefit measures established during the previous analyses were structured into a hierarchical model as shown in figure A4.2.1. The model was arranged so that costs and benefits were kept separate. This would enable them to be assessed against each other later.

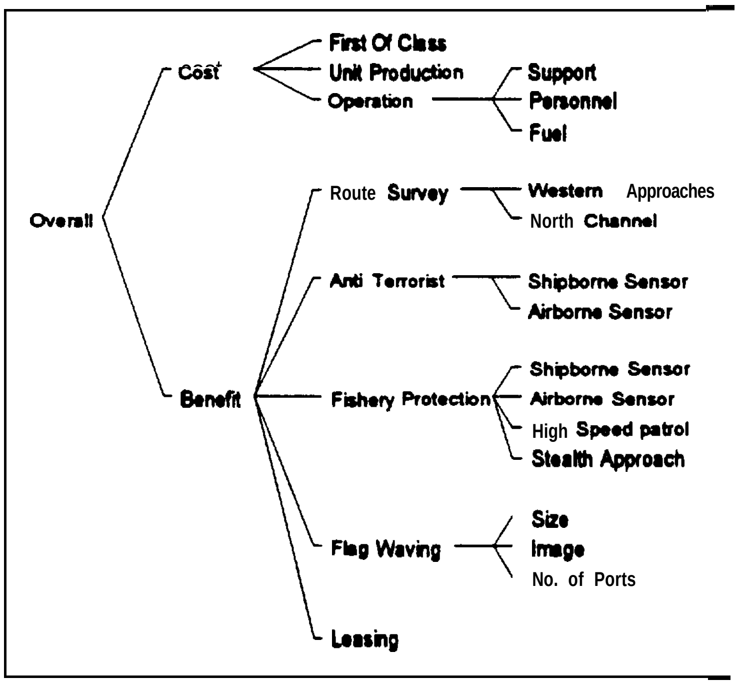

Figure A4.2.1
MAVT Model Structure

- **Determine cost and benefit values**
  The analyses had produced quantitative values for costs and measures of effectiveness. However these measures were not comparable with each other and could not be combined in any direct way. The first step in comparing them was to express them in terms of value to the user. This distinction is important as a linear measure does not necessarily represent a corresponding Linear variation in value. The allocation of values was performed using the judgement and experience of a team of experts who assessed the relative value of each option against each attribute. In most cases a linear attribute measure to preference value relationship was accepted. The resulting preference values ascribed by the team to the costs and benefits were as follows

Cost Preference Values	Surface Effect Ship	Monohull Baseline 55m	Monohull Seakeeping 70m	Monohull Low Cost 40m
First Of Class	24	52	0	100
Unit Production	25	52	0	100
Support	4	51	0	100
Personnel	100	40	0	70
Fuel	0	97	90	100

Note that since the cost values are on a preference scale whereby the most preferred scores 100, then the cheapest options have the highest scores and the most expensive the lowest.

Benefit Preference Values	Surface Effect Ship	Monohull Baseline 55m	Monohull Seakeeping 70m	Monohull Low Cost 40m
Route Survey				
Western Approaches	100	10	17	0
North Channel	100	6	11	0
Anti Terrorist				
Shipborne Sensor	100	14	50	0
Airborne Sensor	100	3	2	0
Fishery Protection				
Shipborne Sensor	100	26	54	0
Airborne Sensor	100	5	12	0
High Speed Patrol	100	8	17	0
Stealth Approach	100	1	3	0

The benefits for the secondary missions had already been expressed in terms of a O-100 preference scale.

- Weight costs and benefits
  During this stage a process was adopted which allowed subjective judgements to be elicited from the team of experts. The judgements were then transformed into a set of weights for the various cost and benefit values. This was achieved by comparing the range of benefit of each attribute with that of the others in turn. Gradually a subjective set of weights was derived which reflected the views of the team. The weights were as follows

Attribute	Weight	Attribute	Weight
Cost		**Benefit**	
First Of Class	10	Route Survey	100
Unit Production	100	Anti Terrorist	80
Operation Cost	50	Fishery Protection	60
Operation Cost		Flag Waving	20
Support	100	Leasing	5
Personnel	43	**Route Survey**	
Fuel	40	Western Approaches	50
		North Channel	50
		Anti Terrorist	
		Shipborne Sensor	10
		Airborne Sensor	100
		Fishery Protection	
		Shipborne Sensor	100
		Airborne Sensor	20
		High Speed Patrol	20
		Stealthy Approach	40
		Flag Waving	
		No. of Ports	33
		Size	33
		Image	33

These weights, derived on a scale of O-100 for simplicity were then normalised and applied to the model. This ensured that the correct weights were applied to each branch, ie. the sum of weights at each node equalled 100.

Determine cost effectiveness

The first step was to plot the cost and benefit figures on a plot, figure A4.2.2. It should. be noted that preference scales were used where 100 represented the most preferred ie. the most beneficial or cheapest.

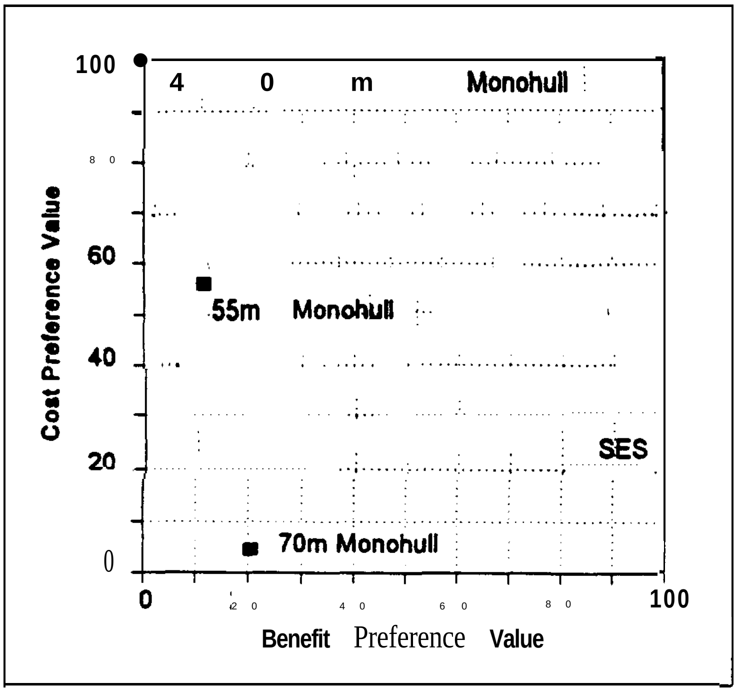

Figure A4.2.2
Preference Cast Benefit Plot

This plot indicated that the two most promising options were the SES and the Low Cost Monohull. The longer Seakeeping Monohull did not seem worthy of further consideration. Thus far the weighting between cost and benefit had not been considered. When it was set at 50/50 an overall cost effectiveness score was derived enabling a possible selection to be made between the two most promising options

Vessel Option	Cost Effectiveness Score
Surface Effect Ship	60
Low Cost Monohull (40 m)	50
Baseline Monohull (55 m)	33
Seakeeping Monohull (70 m)	13

Before too many conclusions were drawn it was important to examine the sensitivity of the model to the selection of weights. The most contentious weight was the balance between cost and benefit and figure A4.2.3 shows how the preferred option changed from the SES to the Low Cost Monohull as the weight on cost was increased from 0 to 100.

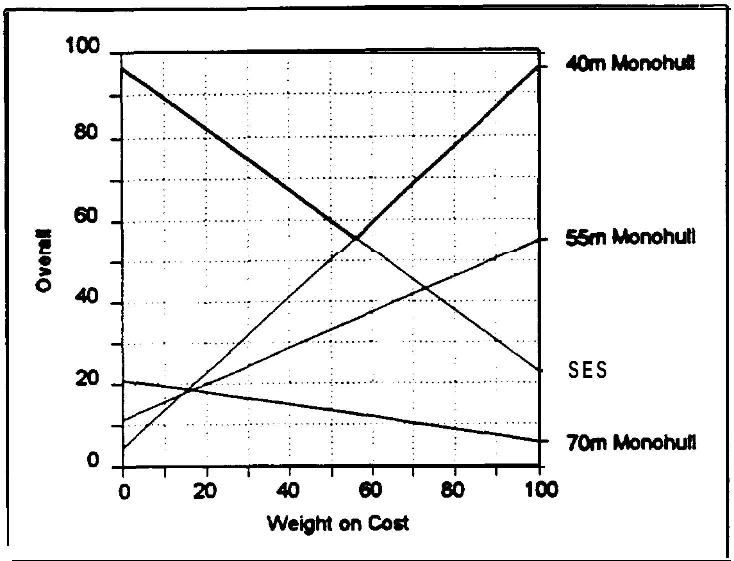

Figure A4.2.3
MAVT Cost Weight Sensitivity Plot

This shows that the selection decision is sensitive to the choice of weight on cost as opposed to benefit. This is not unusual and can generally be resolved by consideration of wider budget implications. Either a cost constraint is imposed or a cost trade off with other projects is performed. Similar weight sensitivity plots were produced for other weights and these showed them to be fir less critical to the overall selection decision.

Finally the reasons for one option being preferred were clarified. This could have enabled an apparently inferior option to be redesigned in order to eliminate weaknesses or alternatively focused more effort on the key advantages of the preferred option. in order to facilitate this the attribute-s were listed in order of weighted difference between the SES and the Low Cost Monohull as follows

Attribute	Weighted Difference
Anti Terrorist, Airborne Sensor	13.72
Route Survey, Western Approaches	9.43
Route Survey, North Channel	9.43
Fishery Prot'n, Shipborne Sensor	6.29
Fishery prot'n, Stealth Approach	2.52
Anti Terrorist, Shipborne Sensor	1.37
Fishery Prot'n, Airborne Sensor	1.26
Fishery Prot'n, High Speed Patrol	1.26
Flag Waving, Image	1.26
Operation Cost, Personnel	1.10
Leasing	0.94
Flag Waving, Size	0.53
Flag Waving, No. Of Ports	-1.26

Attribute	Weighted Difference
First Of Class Cost	-2.38
Operation Cost, Fuel	-3.42
Operation Cost, Support	-8.20
Unit Production Cost	-23.44

Some conclusions were drawn from this analysis

- Assuming an equal weighting on Cost and Benefit the SES was the preferred option.
- If Cost became the most important consideration then the Low Cost Monohull was the preferred option.
- The extra sealceeping performance of the longer monohull provided no real increase in mission effectiveness. The reduction in effectiveness of the shorter monohull was more than offset by the cost savings obtained.

A4.2.3 **References**

1. Winter, N.J., Bond, S. A., Courts, M. D.
"A Cost/Benefit Comparison of a Monohull and a Surface Effect Ship Route Survey Vehicle using XOPEVAL"
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