UNIVERSITY OF SOUTHAMPTON

A CONCEPT DESIGN AND DECISION MAKING MODEL FOR ALTERNATIVE HIGH-SPEED FERRIES

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ABSTRACT

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Decision making in the fast ferry market is a complex issue. A new approach has been developed to address this in a concept design framework. This comprises two major parts: a technical design framework and a decision making model.

The technical design framework is developed using a flexible modular structure, allowing the quick generation of feasible designs which are then compared using the decision making model. One of its major characteristics is that it uses a novel area-based approach for the generation of a set of main dimensions, based on carrying capacities alone. As high-speed ferries are a relatively recent development, there is a sparsity of available systematic data and relevant techniques. Most major calculations are therefore performed using specialised data and tools created within the University of Southampton, most of them as part of this research programme. This allows the full investigation of the two most common hull configurations, namely monohulls and catamarans, which make up the majority of fast ferries.

The decision making model is developed in view of the special characteristics of the fast ferry market. The performance of competing designs is defined in such a way that a better alternative is one that better satisfies passenger preferences and requirements and therefore has higher potential for commercial success. This is reflected in the selected set of primary attributes which define the performance of each design; this includes attributes representing seakeeping performance, passenger comfort and accommodation quality, as well as straightforward economic attributes. Fuzzy sets are used, allowing a uniform quantification, modelling and normalising of all these diverse requirements and the corresponding attributes. The model focuses on the concept of design robustness by applying an algorithm based on a Taguchi-type approach. This is the first, to the best of the author's knowledge, application of such a method for ferries. Finally, a further major feature of the model is its ability to cope with different vessel types; the decision making algorithm, which can be used separately, is developed in such a way that designs of all hull forms and types can be defined, compared and ranked simultaneously.

Example applications have been set up and run in order to test the various parts of the framework as well as the overall approach itself. These have indicated that the developed approach can be successfully used to generate a number of alternative high-speed ferry designs and make a final choice among them with significant speed and reasonable confidence in the results. It is believed that this new decision making approach represents a powerful tool for the early concept design stages.

CONTENTS

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PREFACE

In this thesis a novel methodology is presented which addresses the concept-stage design and the related decision making problem for alternative high-speed ferry types. It is therefore structured in the following way: Chapters 1 to 4 are introductory chapters giving the necessary background to the problem and the proposed approach; Chapters 5 to 8 form the main part of the thesis and describe in detail all the aspects of the developed framework; and Chapter 9 forms the concluding part of the main text of the thesis. Appendices follow which include information on the data, techniques and tools which have been used, both already existing and created as part of this research programme.

Chapter 1 offers a brief introduction, discussing the main aims and the scope of the research. In Chapter 2 an insight on the current status in the field is given together with a review of relevant literature; these help indicate the necessity of new research in this field. In Chapter 3 the major practical issues concerning high-speed ferry design and decision making are discussed in more detail. The shortcomings of available design data and techniques, as well as available decision making approaches and related practical considerations, are also discussed. These demonstrate the need for a new approach. Finally, Chapter 4 offers an outline description of the approach which was developed as a result of the above-mentioned considerations.

In the following chapters this approach is presented in detail. This comprises two major parts, namely the technical design framework and the decision making model. Chapters 5 and 6 are concerned with the former while the remaining Chapters 7 and 8 focus on the latter.

Chapter 5 describes the modules of the technical design framework which allow the calculation of all the principal characteristics that define a feasible technical design. Then in Chapter 6 the calculation of the performance characteristics which indicate the relative merits of competing designs is discussed. These include costing and seakeeping characteristics which depend on the route and overall operating scenario in general.

The decision making model is presented in Chapter 7. This includes the selection of the set of primary attributes to describe the quality characteristics of competing designs, the use of fuzzy sets to uniformly quantify and normalise these attributes and an outline of the sensitivity analysis which is of great importance for high-speed ferries. The main part of the thesis concludes with Chapter 8 which presents the final selection methodology, including the systematic generation of designs and scenarios as well as the definition of the overall ranking criterion. A comprehensive example application and discussion is also included in this chapter.

The main text of the thesis is completed with the final conclusions which are given in Chapter 9. This includes recommendations for further research on the subject.

The appendices which follow include detailed information on the data and tools that have been used. Some of these had already been developed at the University of Southampton and elsewhere, while a significant amount were created as part of this research programme, including statistical data and computer programs. Brief summaries are also given of theories and techniques which were applied, such as fuzzy set theory, Taguchi's method and design of experiments using orthogonal arrays.

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NOMENCLATURE

A_E/A_0	Propeller blade area ratio
A_P	Total passenger area
A_S	Seating area
A_V	Vehicle area
B	Beam
B_H	Catamaran hull beam
BM	Metacentric radius
C_B	Block coefficient
C_C	Catamaran building cost
C_D	Diesel engine acquisition cost
C_F	Friction resistance coefficient
C_{GB}	Gearbox acquisition cost
C_{GT}	Gas turbine acquisition cost
C_M	Monohull building cost
C_R	Residuary resistance coefficient
C_S	Wetter surface area coefficient *or* Semi-SWATH building cost
C_{WJ}	Waterjet acquisition cost
CRF	Capital recovery factor
D	Depth *or* Propeller diameter
E	Equipment numeral
F_n	Froude number
F_∇	Volumetric Froude number
GM	Metacentric height
K_Q	Torque propulsive coefficient
K_T	Thrust propulsive coefficient
KB	Vertical centre of buoyancy
KG	Vertical centre of gravity
J	Advance coefficient
L	Length
L_{OA}	Overall length
L_{WL}	Waterline length
m	Membership grade
N_P	Passenger capacity
N_V	Vehicle capacity
NPV	Net present value
P	Propeller pitch *or* Installed power
P_B	Brake power
P_D	Delivered power
P_E	Effective power
R^2	Correlation factor
R_n	Reynolds number
R_T	Total resistance
RFR	Required freight rate
S	Catamaran hull separation
t	Thrust deduction
T	Draught
V	Speed
V_S	Service speed
w_t	Wake fraction
W_D	Diesel engine mass
W_{GB}	Gearbox mass
W_{GT}	Gas turbine mass
W_{GTM}	Total gas turbine module mass
W_{WJ}	Waterjet mass
Z	Propeller blade number
α	Shaft angle
Δ	Displacement
η	Signal-to-noise ratio
η_0	Propeller open water efficiency
η_D	Total propulsive efficiency
η_H	Hull efficiency
η_G	Gearbox efficiency
η_R	Relative rotative efficiency
η_S	Shaft efficiency
μ	Mean value
σ	Standard deviation
∇	Displacement volume

1. INTRODUCTION

Over the past few years there has been a significant growth in the speed and applications of passenger and vehicle ferries employed on short sea shipping routes throughout the world, see Fig.1.1 [1]. This figure shows the market growth between 1990 and 1995, but the growth has been even bigger since then. This has led to developments in new vessel types suitable to meet the needs of these higher speeds including numerous variants of both monohulls and multihulls such as catamarans, SWATHs, SESs and other hybrid vessels. These developments are having a particular impact in Europe, where a significant number of passenger and vehicle routes are suitable for fast ferry operation. The move to higher speeds and new vessel types is already apparent on routes such as those on the English Channel and the Irish, Baltic and Mediterranean Seas amongst others.

Decision making in the high-speed ferry market and selection between competing alternative designs is a complex issue, due to a number of special characteristics this market possesses. The three major concern: (1) the existence of numerous hull types and forms to choose from for any given service; (2) the increased sensitivity of high-speed vessels to variations in external economic and environmental factors; and (3) the subjective nature of the requirements and preferences of passengers, who are the ultimate customers and users of ferries. The method presented in this thesis aims at addressing these issues in a comprehensive manner within the context of concept design, where many important decisions are made.

A programme of research has therefore been developed at the University of Southampton in order to establish an overall framework, or shell, for the conceptual exploration and evaluation of alternative high-speed ferry types. Concept exploration models can be used for the systematic search of the design space for the 'best' starting position for a more detailed design. As such, the approach also offers a means of comparing the 'best' of alternative or competing vessel types.

For most commercial vessels the selection of the most appropriate design for a given service can be based on a set of technical and economic features which are quantifiable and indicate the relative merits of competing alternatives. On the other hand, the attractiveness of competing ferries and therefore the selection between them does not depend solely on clearly defined technical aspects that can be easily quantified and compared. For these craft, unlike cargo vessels, commercial success depends, to a great extent, on their ability to attract passengers; this ability is not always easy to quantify and may depend not only on technical or other attributes but also on subjective preferences that vary from one passenger to another. In the proposed method the performance of competing designs is therefore defined in such a way that a better alternative is one that takes into account the preferences/requirements of passengers and therefore has higher potential for commercial success. Alternative designs are defined using a selected set of primary attributes which can determine the ability of each design to attract passengers and therefore its potential for commercial success. Fuzzy sets are used for the uniform quantification of all attributes, which allows a direct comparison and ranking of competing alternatives to be made.

Another particularly important issue concerns the uncertainty about the variation of external factors during the vessel's economic life. For example, fuel costs significantly affect the economics of high-speed transportation and the effect of variations in fuel prices, which can be expected during a vessel's economic life, on competing vessels should be examined. Also, seakeeping performance is a very important issue for ferries, particularly high-speed craft, and the implications of transferring a vessel to different routes, which is quite common for fast ferries, should be examined as well. Performing a comprehensive sensitivity analysis is therefore an issue of great importance. The proposed decision making model includes a comprehensive sensitivity analysis which is based on the concept of design robustness by applying a Taguchi-type approach. This allows the identification of the best among alternative designs as the most robust, in other words the one that would maintain its good performance should external uncontrollable factors vary, which they probably will.

As mentioned earlier, decision making becomes even more complicated for fast ferries as a result of the existence of various hull types and forms. Numerous monohull and multihull variants are available for high-speed ferry applications, each possessing distinctly different characteristics; this makes the comparison and selection of the best alternative more complex and difficult. For this reason the decision making model is structured in a way that allows for designs of any possible or desired configuration to be compared and ranked without any implications in its use and implementation.

There are two major aims in this programme. The first has been to establish a flexible modular framework for the development of concept exploration models of relevant short sea high-speed ferry types. This has entailed the development of a global design model for the derivation of the technical attributes for each vessel type, as well as the definition of the economic characteristics of each particular vessel. The second major aim has been to explore and propose suitable evaluation and decision making techniques when alternative competing vessels or vessel types are being considered for a particular service. This is an important part of the problem as it is in this particular area that there is a lack of techniques and experience.

The final outcome is an integrated global model which uses the basic operational requirements set by an operator for a specific service as input, as would normally be the case in practice. The concept design framework uses this input and creates a number of alternative feasible designs, which may be of the same or different hull types. These designs are then analysed by the decision making framework, which eliminates the ones whose performance is not satisfactory and then selects among the remaining designs the one which is considered most suitable for the particular service under investigation. It is apparent that the very definitions of a 'satisfactory performance' and the 'most suitable design' are not a priori determined and they are among the most important and fundamental goals of the development of the decision making framework. Fig.1.2 gives a schematic overview of such a global model, which is described in detail later.

It is apparent that an implicit requirement for the model is to be able to cope with as many different vessel types as possible. At present the scope of the model, as far as the technical design is concerned, is limited to monohulls and conventional catamarans only. These two vessel categories make up the vast majority of operating fast ferries around the world and have the highest growth rates, see Fig.1.1; they therefore form a good basis on which to establish the methodology. It will be desirable, depending on the availability of data and tools, to incorporate more vessel types into the model in the future.

2. BACKGROUND

2.1. Current Status

The rapid growth of the fast ferry market, in terms of number and size of operating vessels as well as number of alternative vessel types available to operators, has resulted in increased complexity in choosing the most suitable vessel for a particular service. It is apparent that there is a need for research in this area.

A number of concept exploration studies for individual ship types have been carried out and published, e.g. [2-9]. However, the comparative assessment and evaluation between different vessel types has not, as yet, received similar attention. Some investigations into competing vessel types for a specific role have been undertaken, e.g. [10-17], but this is significantly different to a global model able to cope with a range of ship types and possible services. It is apparent that, with the growing number of alternative vessel types available for the fast ferry market, research in this area and the development of decision making tools and capabilities are necessary.

There are several tools allowing the derivation of a full set of a ship's technical and commercial attributes, yet few address the further implications of using these in order to compare the merits of competing designs, especially if these are of significantly different types. Furthermore, it is apparent that the decision making process in the fast ferry market is fairly complicated and not always rationalised, and the methods used by operators in reality are varied, complex and difficult to model. This research programme was initiated with the aim of addressing this subject and defining possible ways of arriving at rationalised solutions. It is for this reason that contacts with designers, shipbuilders and operators have been established, which have provided valuable insights into the adopted practical procedures.

Available historic and systematic data for high-speed craft are limited. Such data had therefore to be created during the development of the framework. These include the large database of high-speed ferries incorporating information such as capacities, sizes, hull ratios, technical specifications and general arrangements, as well as various other technical databases concerning for example structural and machinery weights and costs and other relevant techno-economic data.

However, these data are not always complete or adequate for the needs of the concept design framework. It would therefore be desirable if they could be enhanced through the use of theoretical tools. Such tools are under development at the University of Southampton and elsewhere, involving structural, hydrodynamic and propulsion issues among others. The synthesis of various analytical tools into the overall framework is seen as a strong point of a model such as the one under development, as it allows the use of both experience, through the creation and use of reliable databases, and innovation, through the incorporation and synthesis of analytical tools to enhance these databases. Adopting such an approach is seen as very important, being the only way to take advantage of these two conflicting qualities. The development of the framework has therefore aimed to make it flexible enough to allow the incorporation of theoretical techniques.

It is apparent that it is in the decision making related to high-speed ferries where research is lacking and therefore more necessary. It is therefore considered that this part of the research programme is very important. In fact, the decision making tool could even be used separately to compare designs created by other design tools or even existing designs available in the market. Of course in such a case all the information which is necessary for the application of this particular decision making approach might not be available; internally generated designs would have the advantage of better compatibility with the requirements of the decision making framework. The only disadvantage in the latter case is the existence of limitations in the range of designs that can be created by this tool, due to the use of systematic series which by default cover finite ranges of hull forms and parameters. These will be discussed in more detail in later chapters.

2.2. Literature Review

A survey of relevant literature on fields related to this research programme follows. This includes papers and books on various aspects of design, particularly in the conceptual and preliminary stages, and on the decision making problem. There is relatively little literature that can be considered of direct relation to the developed approach. However, the studies and research reviewed offer useful background information and interesting ideas; this has some practical value and the present review is carried out in this context.

2.2.1. Early Papers

The first published studies that need to be mentioned here started appearing in the late 1970s. Classic early papers include those by Watson and Gilfillan [18] and Carreyette [19]. The former is noted mostly for the much used formulae and factors for initial weight estimations. These are however developed for conventional commercial vessels; much caution and possible alterations are necessary if they are to be used for fast ferries. Similarly, the latter paper is noted for the thorough investigation into preliminary cost estimations. Although the 1977 data and factors may be of no practical significance now, it is the applied methodology that still makes this paper a useful reference.

At the same time, Eames and Drummond produced the first significant paper on concept exploration [2]. They address the important issues of tool-designer interaction and also parametric and sensitivity analysis. Shortcomings of this paper, when seen in the context of the current project, include the fact that it focuses on warships (for which the design priorities are different); inadequate modelling of seakeeping aspects; and finally its scope, which is restricted to one ship/hull type only. Similar limitations on the same three issues are noted for the Nethercote and Schmitke paper [5], which is involved with naval SWATH vessels.

2.2.2. Concept Exploration and Design Philosophy

Twenty years on, the problems encountered in concept exploration and conceptual or preliminary ship design have been addressed by a number of people around the world. Andrews has presented a number of papers (e.g. [20-21]) which address fundamental aspects such as the overall philosophy and management of design, as well as the importance of synthesis in design, focusing however on naval vessels.

An important reference on the management of design is the book by Erichsen [22]. In this book he addresses various aspects of the design process and how it should be managed, including the important issue of market research and selection as well as designing for a specific market.

Hockberger [23] introduces the concept of the ship as a system, comprising a number of subsystems but at the same time being itself part of a larger supersystem whose optimum performance is the ultimate design goal. Although this paper too is military-oriented, in which case the supersystem includes for example the task force the ship is part of, the concept can be applied to commercial vessels as well, which can be seen as parts of a larger transport network for passengers and/or cargo. This is particularly relevant for high-speed ferries which are at this period seen, at least in Europe, as alternatives to land transport but at the same time as part of an overall intermodal transport infrastructure. The paper addresses the aspect of the ship's performance and effectiveness in such a broader context.

2.2.3. Design Tools and Methodology

A number of design tools have been published, e.g. [3-4], [7-9], [31]. Not all of them focus on high-speed ferries, they do however prove to be useful references, as they describe the overall structure of the models, including selection of parameters and attributes. Werenskiold's paper [3] includes some regression plots for high-speed slender catamarans. The paper by Grosjean et al. [7] is significant in that it addresses the design of high-speed catamaran ferries from an operational and economic point of view. Pal and Doctors investigate the design of high-speed river catamarans in [9].

Apart from general design tools, papers describing the preliminary design of specific vessels are also interesting, because they provide information and data as well as insight into the design process which may not be gained from commercially developed vessels. Some designs for high-speed vessels are presented in [6], [15], [24-30]; these include multihulls of various types, such as trimarans, SESs, SWATHs and semi-SWATH catamarans, whose tasks include the transportation of cars and passengers as well as cargo in the form of containers. Some of these papers, such as [25-30], also include information and insights on techno-economic issues concerning transport efficiency and overall logistics of the proposed designs, which makes them more interesting.

A particularly important issue for high-speed craft is that of weight estimation, which is addressed in the paper by Daidola and Rayling [32]. They introduce the concept of weight engineering for detailed weight calculations, however they focus mainly on monohulls and pleasure craft. Also, the regressions given for fast ferries cover only a small number of small such vessels, they are therefore of little if any relevance to the needs of the current project.

2.2.4. Knowledge-Based Systems and Neural Networks

Knowledge-based or expert systems may be of great importance for the development of concept exploration and design models. Welsh et al. describe such a system in [33], which is applied in the design of containerships. This paper addresses the issue of the creation of a reliable database, which is of paramount importance for such systems. It also discusses the potential of fuzzy sets for modelling the concept of uncertainty in the design process. Van Hees [34] addresses the subject in a more general context and focuses on the flexibility expert systems can offer. It is noteworthy that in both these papers the authors address the issue of innovation, which is seen in general as the opposite of what can be expected to be achieved by using expert or knowledge-based systems.

Another two concepts which are related to that of expert systems are fuzzy logic and artificial neural networks. Some examples of such applications can be seen in [35-38]. It was decided that, within the scope of this project, these techniques would not be explored further.

2.2.5. Transport Efficiency and Economics

Economic aspects are known to be important for any maritime operation and this is exacerbated in the fast ferry market where the vessels are particularly costly to build and operate. It is only natural therefore that this subject has received much attention. In a very significant paper [39] Akagi addresses the aspects of transport efficiency and economy in a synthetic way, focusing on high-speed marine vessels in comparison with other sea, land and air transport modes. Similarly, in [40] Psaraftis et al. and in [41] Schinas and Psaraftis investigate the potential of introducing high-speed ferries in a market currently dominated by conventional tonnage and air transport, as well the implications of integrating such craft in a broader intermodal network.

Wergeland and Osmundswaag [42] focus their investigation on the European shortsea shipping network, which is in general seen as a promising area for expanded use and application of high-speed ferries. Similar studies had also been undertaken in the USA in the 1980s, e.g. [43]; however, as reported in this paper, the market there is not particularly suited for fast ferry operations and this is reflected in the fact that even now such craft have yet to play any significant role in the American shortsea shipping network.

The importance of service quality as well as speed and travel times is emphasised in the paper by Foss [44]. He also discusses the economic implications of various factors such as ports, fuel costs, maintenance and operation in general, as well as initial investment and output/income. Hockberger on the other hand presents an economics-based integrated framework, in which he applies his total-system approach [45]. An overall discussion of the subject, taking into account performance characteristics, transport and commercial efficiencies and market characteristics is given by Wright in [46]. In this paper he also addresses the issue of subjective factors, which may be important in the case of passenger ferries, as well as the economic implications of environmental and safety issues.

2.2.6. Design Robustness - Taguchi's Method

A concept which has appeared relatively recently in marine applications and offers great potential for the selection between competing designs is that of design robustness. Taguchi's method is a useful tool for such studies and an introductory description of the related theory together with an example is given by Huseby in [47]. In [48] Grubisic et al. present a design model which uses this theory and performs unfeasible design elimination, sensitivity analysis and calculation of a measure of robustness in order to select the most suitable design. The modular construction of the model and an example application are also described in the paper. In [49] Trincas offers a comprehensive example application in the area of Ro-Ro subdivision; another example application of the method is given by Unal and Dean in [50].

There is extensive bibliography on Taguchi's method, which includes numerous books both by Taguchi himself, e.g. [51], and by other authors, e.g. [52-54]. These books offer comprehensive theoretical background to the method as well as illustrative example applications. Extensive study of this information led to the conclusion that Taguchi's method is highly relevant to the objectives of this research programme and thus to the decision to investigate its use. Fundamental to the application of the method is the concept of orthogonal arrays. Information on these as well as lists of standardised ones are given in [54-55]. Alternatives to Taguchi's approach are given in [152] and are discussed later.

2.2.7. Comparative Studies

As mentioned earlier in the text, some comparative investigations have been undertaken, although mostly limited to comparisons in the context of specific services. Ozawa et al. offer insight into the concept design stage of the 'Techno-Superliner' project, including basic specifications and requirements [10]. Goubault et al. present some comparative parametric studies of monohull and SES vessels, describing the methodology, definition of parameters and standards/criteria, as well as some design trends [11]. The potential of various types of high-speed marine vehicles for the Mediterranean Sea is investigated and evaluated by Trincas et al. in [12]. In a different context, the feasibility study of a high-speed catamaran and a comparison with an existing well-established monohull are presented in [13] by Trincas et al. The economic comparison and design process are described together with the definition of variables, parameters, attributes and constraints.

Day et al. [14] discuss the concept evaluation of different hull types for large very-high-speed vessels but they focus on hull optimisation for minimum resistance and their considerations may be seen as incomplete. Lavis et al. investigate the potential of SESs, ACVs, hydrofoils and SWATHs for naval roles, describing the concept design process, parametric studies and assessment methodology in [16]. Finally, Gee and Dudson [17] present a model which addresses operating economics aspects of monohulls and catamarans, discussing parametric changes and sensitivity analyses, mainly on speed and engine type. It should also be noted that the SWATH design presented in [15] is compared with existing vessels.

In [56]Aláez et al. compare two monohull fast ferries, but the comparison is limited to their seakeeping performance; also the two vessels have rather similar hulls. However the paper is interesting because they describe the set-up of their test. Similarly in [57] Sariöz and Narli compare the seakeeping performance of a round bilge and a deep-vee hull form. This paper however is concerned with naval vessels. Naval vessels are also examined by Sadden and Nisbet in [58], however the scope of this paper is broader in the sense that they investigate a wider variety of hull forms, including monohull, catamaran, SWATH and trimaran.

It is apparent that all these studies have shortcomings in the context of relevance to the current project. Most of them focus on the comparison of specified designs for given roles. This is significantly different to the objective of this project which is to cope with a range of alternative designs as well as a range of possible operating scenarios. In general the studies which are concerned with naval vessels are more comprehensive in this sense, however in this case the relevance is also lost as naval vessels have fundamentally different requirements and considerations affecting their design and decision making process.

2.2.8. Decision Making Methods

The decision making problem is complicated and published literature on it is relatively limited. Some interesting ideas can be obtained from two significant papers which focus on the seakeeping performance and the development of relevant criteria. In [59], Graham et al. introduce the concept of MIIs and their degrading effects as major parameters, as well as the use of speed polar diagrams to indicate the availability of each vessel and for operation guidance purposes. Bales introduces his innovative ranking index in his classic paper [60]. Although both these papers are involved with seakeeping performance only and just for specific hull types, the underlying conceptual thinking can be generalised and used not only for different hull types but also for the development of criteria for the ranking or decision making in a broad design context. Particularly the Bales-type approach can be used for the development of an overall ranking method for competing designs of various types.

Refs. [6-7], [11], [15], [27], [31] and [48] among others do address the decision making problem and the use of the multiple criteria approach. This method has received much attention in recent years and there are a number of publications focusing on it. An important discussion on various available approaches within the multiple criteria decision making framework is given by Stewart in [153]. In this paper the author offers a critical review of such approaches and an in-depth discussion on their strong points and shortcomings.

An early presentation of the method and necessary definitions can be found in one of the early classic papers on the subject by Sen [61]. Applications of the method in various environments can be found in [62-66]. Sen and Bari [62] address the problem of inland waterway fleet replacement in a developing country, while Lee and Kim [63] focus on LNG carrier design. Trincas et al. focus on the design of fast monohulls in [64] and their paper describes the model structure and methodology, definition of variables, parameters and attributes as well as the development of the various modules. It also addresses the issues of engineering economics, risk and sensitivity analyses and design robustness. Grubisic on the other hand presents a similar model for the design of fast catamarans [65]. Peacock et al. use such techniques for the design of hull forms with minimal motions [66].

Birmingham and Smith [67] as well as Hutchinson et al. [68] combine the application of the multiple criteria method with genetic algorithm search techniques. In the former study, which is concerned with automated hull form generation, the application of a genetic algorithm is followed by the application of a multiple criteria decision method. The paper addresses the issues of search size reduction and search efficiency improvement as well as that of weighting definition. The latter paper is concerned with Ro-Ro survivability and it presents the application of a multiple criteria genetic algorithm followed by a multiple criteria decision method. It also discusses the issues of comparative evaluation and robustness as described earlier, which are highly relevant to this research.

Similarly in [69], which deals with high-speed Ro-Ro concept-stage design, Hutchinson et al. present the overall multiple criteria decision making methodology including a multiple criteria genetic algorithm and a multiple criteria decision making model. The paper also focuses on the concept of evidential reasoning based hierarchical analysis; this methodology offers a powerful tool for the definition of priorities in a reasonable manner, thus tackling the problems encountered with the definition of weightings which is largely subjective and is often made in an arbitrary way.

2.2.9. Passenger Satisfaction and Comfort - Motion Sickness

Passenger satisfaction is an issue of paramount importance for passenger ferries and it has received some attention in recent years. In [70] Eide focuses on the importance of customer/passenger requirements and overall travel quality for fast ferries. He also proposes a method for quantifying these aspects using matrices of comparative importances. It is believed that this issue should be given attention for the reasons discussed in earlier sections of this thesis.

Seakeeping is one of the most important factors affecting passenger satisfaction and some motion sickness studies have also been published in recent years. Smith and Koss [71] present such a study and statistical results and propose a new, and at present incomplete, measure. Takarada et al. [72] present another study and investigate the role and interrelation of various physiological and psychological factors, as well as the potential of using fuzzy integrals to model the problem. In [73] Rocco et al. also focus on the subject of ride comfort considerations for high-speed ferry passengers. Similarly in [74] Grossi et al. discuss the implications of fast ferry passenger comfort considerations at the preliminary design process. The authors investigate the effects of human factors and the development of relevant seakeeping-related comfort criteria. They present a comprehensive parametric investigation and the definition of a seakeeping comfort indicator. The issues discussed in this paper make it a useful reference for the purposes of the current research programme. A study undertaken by a multinational NATO Group [75] focuses on naval vessels but provides useful information on relevant indices concerning issues such as motion sickness incidence and motion-induced interruptions among others.

2.2.10. Priorities / Weightings

The development of priorities (or weightings) may be important for the comparative evaluation of alternative designs. Saaty describes his method of developing priorities in hierarchical structures in his classic early paper [76]. This method is based on a number of pairwise comparisons between the importances of various attributes among competing designs and the creation of relevant matrices. This approach offers a way of rationally addressing the issue and has potential for incorporation into concept design tools, assisting the decision making process. This issue is also addressed in [69-70] where the presented approaches are different, yet similar in parts of their philosophy to Saaty's and to each other.

2.2.11. Fuzzy Sets

Fuzzy set theory provides a most useful tool for the modelling and quantification of subjective preferences and can also prove to be useful in a much broader context. Furthermore the application of fuzzy set theory aids users in customising a system or model according to their specific needs or requirements. An example of its use can be found in the paper by Nehrling [77] which focuses on general arrangement design. It also provides a summary of relevant theory and an example application which illustrates the development of goals and constraints, the definition of weightings and relevant sensitivity analyses and the final selection based on performance-based decisions. A few of the other papers, such as [33], [48-49], [64], also involve the use of fuzzy sets, the application of which has been receiving some attention in the marine technology field recently. In-depth descriptions of fuzzy set theory and applications can be found in a number of books, such as those by Novák [78] and, more recently, Klir and Yuan [79]; [80] focuses clearly on industrial applications where the potential of fuzzy sets had been investigated and recognised much earlier.

2.2.12. Optimisation Techniques

Although performing optimisations, as defined in the traditional sense, is not a primary objective within the context of the present research programme, some minor local ones may be performed in parts of the technical design framework. Such techniques have been widely used for a number of years and are still popular. An early classic paper in this field is that by Fisher [81]. More recent studies include those by van Wijngaarden [82], Keane et al. [83] and van Griethuysen [84] which all focus on naval vessels. Optimisation techniques are also described in papers such as [9] and [14].

All these, as well as other published optimisation studies, have the major shortcoming of a narrowly defined optimisation goal which renders them unrealistic in the context of the fast ferry market. In the latter case the problem is multi-faceted and includes conflicting, often subjective, requirements which cannot be easily compounded into one optimisation goal, at least in the way that this is done in the above-mentioned studies. It should therefore be noted that the shortcomings of such studies are meant not in the sense of their search and optimisation algorithms but mostly in the sense of their oversimplified goals and decision making criteria.

3. HIGH-SPEED FERRY DESIGN AND DECISION MAKING ISSUES

3.1. Available Design Data and Techniques

As has been mentioned in the previous chapters, there is a sparsity of available design data and techniques for high-speed ferries. As these craft represent a relatively recent development, little systematic or empirical data exists that can be used for concept design purposes. Until now the design of high-speed ferries seems in most cases to have been developed in an ad hoc manner.

Concept exploration methodologies that can be found in existing literature, such as that by Eames and Drummond [2], cannot be applied for high-speed ferries for the reasons discussed in the relevant review section. The ability to investigate alternative hull types, which may have significantly different parameters and characteristics, is a fundamental objective of this project; existing concept design models tend not to have that characteristic and this is their most important shortcoming in view of high-speed ferry design.

Apart from overall design methodology, similar limitations exist in the various specific design areas such as weight calculations or costing estimates for example. The two classic studies reviewed earlier, by Watson and Gilfillan [18] and by Carreyette [19], provide useful ideas in terms of the general philosophy which may be applicable in some cases for this project. However the actual data, regressions and formulae are not suitable for high-speed craft.

As far as masses are concerned, the overall situation is totally different for such craft than for conventional cargo vessels which are investigated by Watson and Gilfillan. Lightweight structures and overall mass reductions are of increased importance in order to achieve higher speeds. This results to developments such as the use of lightweight materials, mostly aluminium alloys but in some cases also composite materials, as well as machinery installations with high performance-weight ratios such as high-speed diesels and gas turbines. Furthermore for multihulls there is also the issue of different hull configurations with additional dimensional parameters which makes necessary a refinement of relevant techniques in order to be able to cope with these craft.

There are few more recent studies which include data that may be more relevant to high-speed craft, such as those by Werenskiold [3] and by Daidola and Rayling [32]. Such studies for fast catamarans and monohulls address both the overall design methodology and more specific issues such as mass estimates, however the data they offer are still too limited for the purposes of a global model.

It is therefore apparent that there is a need for development of both new data and new tools as part of this research programme. It is on this area that work on the concept design part of the framework focuses. This entails the generation of data and the creation of relevant tools together with the synthesis of these into a design process also incorporating any other systematic data or analytical tools.

Concerning the latter, considerable work has been carried out and is ongoing at the University of Southampton concerning the performance of high-speed craft. This includes particular work on the performance of high-speed craft in calm water and waves, hydroelastic effects and the applications of lightweight materials and structures, e.g. [85-93]. As a result of such research there are for example systematic data for calm-water as well as rough-weather performance of both monohulls and catamarans which are used in the respective powering and seakeeping modules. It is desirable to enhance these by the use of analytical tools which are currently under development. The incorporation and synthesis of these various analytical tools into the design process would significantly strengthen the concept exploration model allowing the user to place less reliance on historic data. This would broaden the scope of the model which would no longer need to be restricted in the existing systematic data, thus enhancing the opportunities for innovation.

Chapter 5 describes the algorithms for calculations of principal characteristics such as dimensions, powering and masses in view of these considerations; similarly Chapter 6 describes seakeeping performance and costing calculations in the same context. The main requirements that led to the development of such algorithms considering the issues discussed here as well as relevant decision making implications are presented at the end of this chapter.

3.2. Current Trends in Decision Making

An outline of some major points concerning the development of the decision making framework follows. This involves both problems that arise and need to be addressed and possible ways of approaching these. The discussion is carried out in the context of integrating the two frameworks, namely design and decision making, into an overall shell or model.

The basic issue concerns the application of the derived technical and commercial attributes, i.e. how to use them in order to compare competing alternatives. A fundamental objective of the exploration model under development is to generate the technical and commercial attributes and to provide the opportunity to use these in order to compare the relative merits of competing designs according to the needs of a particular situation. There are alternative techniques which are discussed in the context of the fast ferry market and their influence on the development of the exploration model.

3.2.1. Available Approaches

Alternative decision making approaches are available. These usually entail using one of two basic analysis techniques, namely a single criterion or measure of merit or multiple criteria, or some hybrid derivative. The aim in every case is to determine which of the competing designs is better suited for the role under investigation, which can be seen as an 'optimum' design. There is therefore a need to define an appropriate measure of merit on which the comparison, ranking and final selection will be based. This varies between alternative techniques.

Since the fundamental requirement for all commercial vessels is profitability, the chosen measure of merit is often some simple single economic parameter such as RFR (to be minimised) or NPV (to be maximised). Such approaches for particular ship types are well documented, e.g. by Fisher [81], and are frequently applied in numerous studies, e.g. [94-95]. A weakness of this approach lies in the need to incorporate reliable and detailed operational information which may not be readily available, particularly for an overall concept exploration model. Also, the approach does not address problems involving more than one criterion.
Multiple criteria techniques have been used in a number of applications in the marine field, such as [61-69]. In the context of concept exploration, a multiple criteria approach may be used where each of the assembled attributes for a

particular vessel is assigned a priority or weighting and the influence of these is investigated. These techniques have received criticism due to the often subjective nature of the choice of priorities. Another point worth noting is that assigning priorities or weightings to the attributes normally leads to the development of a single criterion, in which case the approach may be virtually reduced to a classical optimisation.

The broad philosophy of the multiple criteria approach does however have attractions at the concept design stage, when complete information may not be available and when it may be possible to assume that certain attributes remain constant between competing designs. The emphasis then rests on the development of suitable groupings of criteria and their weightings. Preliminary discussions with practitioners have, for example, indicated that such a grouping might simply consider vessel size (dimensions), construction cost, fuel costs and seakeeping/ operational percentages. Assembly of suitable weightings for these attributes may depend on both objective and subjective considerations of the user. Various techniques which may cope with these demands have been considered and investigated.

Alternative approaches have also been explored, which mainly attempt to quantify attributes concerning passenger satisfaction, which should be one of the top priorities. A specialised feature of ferries, which evolves from the fact that they carry people, is that the 'attractiveness' of competing vessels and therefore the selection between them does not depend solely on clearly defined technical aspects that can be easily quantified and compared. It also depends, to a great extent, on subjective preferences that vary from one passenger to another. For example, passengers may be willing to pay more to travel on a ship that meets their specific requirements/preferences in a better way, hence it cannot be simply argued that a vessel charging a lower fare would be the best choice.

This renders approaches using a single criterion unrealistic for the purposes of the model. It is considered that simple single criteria such as RFR or NPV do not fully or best characterise the situation for ferries and therefore were not adopted in the present study. The reason is that for such calculations certain assumptions must be made for capacity utilisations. This contradicts the very philosophy of this study where capacity utilisation is in fact seen as dependent on the ability of each vessel to attract passengers; it is this ability that needs to be quantified and defined as some sort of measure of merit which will in turn indicate the potential of each vessel for commercial success in a more realistic way.

It would therefore be beneficial if these passenger preferences could be quantified and weighted, allowing a realistic evaluation of the 'attractiveness' of each vessel, which may strongly affect the prospects of its commercial success. Such approaches have received some attention in recent years, e.g. [70]. In this sense it was decided that a carefully defined multiple criteria type of approach taking into account subjective preferences or requirements and including the facility for performing a sensitivity analysis could offer the best approach. However there are still some practical considerations that need to be taken into account if the decision making model is to be truly realistic in the context of the fast ferry market.

3.2.2. Practical Considerations

Preliminary consultations with designers, shipyards and operators have been held in order to help establish acceptable and realistic approaches which will arrive at viable and practical solutions. In this manner the needs and requirements of the fast ferry market can be more accurately defined and the outcome will be of greater practical value.

The methods used by operators in choosing a particular ship for a particular service appear to be many and varied and it is unlikely that such methods can be modelled in a simple way. This is made more complicated by the fact that in reality the process of decision making does not always seem to be very rationalised. In many cases the criteria used for choosing a particular vessel or vessel type are arbitrarily defined rather than being developed through a rational approach and investigation. It is however apparent that choice must largely depend on a comparison between some of the technical and commercial attributes of competing vessels.

A possible approach considers a limited number of attributes which are assumed to describe the overall technical and commercial viability of the proposals. Full simulations are likely to be too cumbersome at the early concept design stage, when a number of detailed elements of information may not be known. In such circumstances a system using a limited number of attributes which adequately describe the relative economic viabilities of competing designs would be very attractive and could be applied rapidly.

Discussions with operators and shipbuilders would suggest that there is room for research into the applications of less sophisticated approaches. For example, at the concept exploration stage they tend to be interested in readily identifiable attributes for comparison between competing designs. Techniques currently applied by practitioners indicate that there is less emphasis on the need for sophisticated approaches at the concept design/investigation stage. Criteria used by operators for screening purposes have been found to be as simple as the sum of build cost plus fuel cost over a number of years. Such approaches have attractions at the early concept exploration stage and some justification for this form of simplification may be provided, for example, by noting that certain elements of operational cost represent a relatively small part of the overall running costs and/or may be considered to be broadly similar between competing designs.

In such a simplified approach the decision making attributes might be condensed into a limited number of items such as those shown in Table 3.2.1. Building/ repayment cost is mainly commercial and measurable. Fuel cost is mainly technical with a directly measurable commercial consequence. Seakeeping attributes contain a mixture of measurable technical and commercial features, but also include other features which may be difficult to quantify. For example, whilst structural integrity and safety may be considered to be covered by regulatory standards, and power increases for a given speed can be calculated, a practical measure of availability and quantification of the concept of passenger comfort/satisfaction are not easily achieved.

Such an approach seems suitable in the context of the current research programme and it was therefore decided to investigate its implications. It is apparent that the selection of the set of attributes and goals/criteria to be used for the application of the multiple objective decision making must be performed with all these considerations in mind. These must be easy to identify and interpret while at the same time providing comprehensive information for an adequate definition of the alternative designs in view of their potential for commercial success. These are discussed in detail in the following chapters.

3.3. Main Requirements for the New Approach

The discussion included in the two previous sections indicates the main issues that need to be addressed for the development of a concept design and decision making tool for high-speed ferries. These in turn lead to the definition of objectives and guidelines for the development of both the technical design and the decision making frameworks.

It is apparent that the creation of design data and tools is necessary. This defined a number of tasks to be pursued during the development of the technical design framework. These include the following:

- A database of existing high-speed ferries should be assembled; this would assist the setting up of an algorithm for the calculations of main dimensions and areas that would be realistic. It would also provide a basis for comparison and verification of the technical feasibility of generated designs.

- Various technical databases should also be assembled including data such as masses and costs of lightweight machinery installations suitable for high-speed ferries, relevant hull structure masses and costs, as well as total building costs of such craft. These would enable the development of tools for relevant calculations.

- Available systematic data should be used to the maximum extent possible. These include resistance and seakeeping data developed at the University of Southampton for high-speed craft in addition to existing series data. It should be noted that these data are restricted to round bilge hulls and are therefore limited for application to monohulls and conventional catamarans only. These vessels do however represent the majority of operating high-speed ferries around the world.

- Analytical tools should be incorporated into the design process if possible. The synthesis of such tools would allow the investigation of different hull forms and configurations as well as broader ranges to expand the already included series. This would be a desirable enhancement of the scope of the model as it would then be able to depart from the existing range defined by the historic database and to cope with generating and investigating designs of various hull types.

Similarly a number of guidelines for the development of the decision making framework emerged. These were indicated by the investigation of available methods and techniques and the consideration of practical issues and include:

- A limited set of primary attributes should be selected in order to describe alternative designs. This set should be small in number and the attributes should be easily identifiable in practical terms. At the same time however this set should offer a comprehensive definition and description of each design in terms of its potential for commercial success. Account must also be taken of aspects such as possible correlations between attributes (also criteria) which should be avoided as is well documented for multiple criteria methods.

- Since the ability to attract passengers and therefore achieve high capacity utilisations and generate high income depends on satisfying passenger preferences and requirements, these should be properly modelled and quantified. The selection of the set of primary attributes should then take this consideration into account.

- An appropriate ranking criterion should be defined by compounding all the attributes. This allows the investigation of conflicting requirements as is well documented for the multiple objective decision making approach. However the existence within the set of primary attributes of those of a significantly different nature may create additional complications. Care must therefore be taken in the application of appropriate techniques.

- It is of great importance to include a comprehensive sensitivity analysis allowing the final selection between competing alternatives. Possible ways should therefore be investigated to set up such an analysis which would allow the selection of a truly optimum design based on a comprehensive investigation of possible uncertainties rather than on relative performances simply in one basic scenario. It should be noted that this analysis focuses on uncertainties relating to possible external factor variations during a vessel's economic life rather than possible uncertainties in the quality of the available design data.

All these requirements need to be combined into main objectives on which the development of the new approach can be based. This is outlined in the following chapter which is then followed by the core chapters which describe in detail the way these issues have been addressed.

4. DEVELOPMENT OF THE PROPOSED APPROACH

4.1. Main Objectives

Taking into consideration the requirements outlined in the previous chapter, the main objective of the new approach is to create an integrated framework for generating a set of alternative feasible designs for a particular given high-speed ferry service and selecting the most suitable among these. The initial input should be a set of operator's requirements in the form of a chosen operating profile, which would normally be the case in practice. Also, the model should be realistic and practical with easily identifiable goals and attributes.

The technical design framework must be robust, using a number of reliable databases together with systematic and other technical and commercial data. At the same time it must be flexible, with a modular structure which will allow the databases and design modules to be constantly updated to incorporate any emerging statistical or experimental data and analytical/theoretical tools. This will enhance the strength of the model and enable it to keep pace with future developments in the fast ferry market.

The decision making framework must be able to model subjective or not easily quantifiable attributes and to combine conflicting requirements and attributes of significantly different nature into an overall ranking criterion. It must also be able to cope with uncertainties by incorporating an appropriate sensitivity analysis.

Despite the integrated approach, the overall model can also be seen as consisting of two parts, namely the concept design and decision making frameworks. This means that if a number of alternative designs are available, be they generated by another model or actual existing designs, the decision making model can be used independently in order to choose between those designs. For this to be possible the attributes which are necessary for the initiation of the decision making algorithm need to be known for each design.

It became apparent that Taguchi's method [51-54], with appropriate minor modifications in order to suit the particular problem, and combined with a multi-criteria approach [61-69] and the use of fuzzy sets [78-79] might offer a suitable approach and would therefore be investigated, as it adequately addresses the major objectives listed earlier. Alternatives to the Taguchi approach do exist, having resulted from critical investigations to the shortcomings of this specific approach [152]. These mainly involve response surface procedures and include alternative formulations of the selection criterion to the signal-to-noise ratio, taking into account the mean and variance simultaneously but separately, as well as different set up of the experiments using alternatives to the orthogonal arrays used by Taguchi for both the control and noise factors. Taguchi's approach is considered to be appropriate, or adequate, for the purposes of this project, for the reasons discussed elsewhere in this thesis, and this led to the decision to use it without further in-depth investigation of other alternatives, the existence of which is however noted.

4.2. Definition of Key Terms

The reason Taguchi's method was seen as likely to be best suited for this application is that it allows the rapid systematic generation of a set of designs and a set of scenarios within an integrated algorithm, including the final choice based on design robustness. It can therefore cope with all the major objectives of this research programme. Here it is combined with the multiple objective decision making method for the reasons discussed earlier. The major relevant terms are defined here in the context of their use for this application so that a description of the overall algorithm can follow. A brief background to the method is also given in Appendix D.

Orthogonal arrays (OAs) hold a key role, allowing significant reductions in the size of the problem to be achieved. This is possible through a systematic tabulation of combinations of parameter/factor values which results in a total number of combinations a few orders of magnitude smaller than those created by a full factorial. This small number of combinations is created in such a way that it allows for a comprehensive examination of the whole available range. This is achievable through the orthogonality between the columns which results in the generation of combinations that are as different to each other as possible, thus eliminating the generation of similar alternatives and covering the whole available parameter range efficiently with a small number of combinations. There are numerous standardised orthogonal arrays, lists of which can be found in [54-55].

Control Factors (CFs): These are in effect the design parameters whose variations define the set of systematically created designs. In ship design problems these can include, for example, hull ratios and other configuration parameters, but their selection depends on the nature of each specific application. They are therefore each given a number of values (levels) within a specified range and different designs are generated by the various combinations of these values, tabulated in orthogonal arrays. These parameters are usually such that they directly influence the output attributes which form part of the objective (quality) function.

Primary Attributes are selected so that they can adequately describe each design, indicating its relative merits in the context discussed in the previous section. These are therefore technical, economic or other attributes which indicate each design's attractiveness and subsequent potential for commercial success.

Fuzzy Sets help to quantify subjective language terms, but they have also proved to be useful in a wide range of applications where they allow a uniform quantification of different attributes so that an overall ranking criterion can be developed. This offers significant advantages for this application and they are therefore used here as they have advantages in both these contexts. This is shown in detail in chapter 7.

Quality Function (QF): This indicates the overall performance of a solution or design with respect to satisfying the given requirements in a specific scenario. It is therefore a ranking criterion the definition of which depends on the specific application and which is calculated directly or indirectly from the defined attributes. Depending on the definition and structure of the problem, the goal may be for it to be as large as possible (maximum), as small as possible (minimum), or as close as possible to a certain central value (nominal).

Noise Factors (NFs): These are external factors that cannot be controlled by the designer and may vary in ways that cannot be predicted at the design stages. It is exactly the presence of such factors that creates the need for robust designs and makes necessary the development of such sensitivity analyses. They are assigned values and tabulated in orthogonal arrays in the same way as control factors. These systematic variations of noise factors lead to a range of different results (values of the quality function) for each alternative design, which in turn allows the robustness of each design to be determined.

Signal-to-Noise Ratio (S/N): This is a measure of the robustness of each design and therefore the final output variable that defines the best choice. The S/N ratio indicates the stability of each solution, i.e. it is higher when a design's performance varies less between different scenarios while at the same time remaining at high levels. The design with the highest S/N ratio is therefore the most robust and in most cases will be selected. It should be added that cases can exist when performance on its own may be more important and the robustness criterion may be of secondary importance. The user or decision maker should be given the option of making this decision and this was taken into account during the development of the presented model, as will be discussed later in relevant sections. The S/N ratio is a criterion that takes into account both the average performance and the relevant variance, allowing a selection which might not have been straightforward otherwise. As with the objective function, there are also three basic corresponding types of signal-to-noise ratios, depending on the nature of the problem: 'larger is better', 'smaller is better' and 'nominal is best'; these have different mathematical definitions. Limitless varieties of S/N ratios can be defined in principle [51-54].

4.3. Outline of the Selected Approach

After all these significant parameters are defined for the specific application under consideration, an appropriate algorithm should be set up. This is to some extent standardised for Taguchi's method but variations may be introduced in different applications. The suggested algorithm for this particular application in high-speed ferry selection is as follows (see also Fig.4.3.1):

1. Generate a number of designs by varying the control factors. These designs are defined by the seven primary attributes as described in Chapter 7. The number of control factors as well as their degrees of freedom (number of levels each factor takes) define the size of the orthogonal array to be used.

For each design:

2. Calculate the value of the quality function for each combination of noise factor levels - the number of noise factors as well as their degrees of freedom will define the size of the orthogonal array to be used;
3. Calculate the value of the signal-to-noise ratio.

4. Select the design with the highest S/N ratio. This is the best design among those tested.

5. Perform an additional cycle (steps 1 to 4) using levels of the control factors around those that form this better combination. The first cycle allows a direct initial elimination of unsatisfactory designs, i.e. designs that fail to satisfy the set requirements for at least one scenario.

After completing the second cycle:

6. Plot the variation of S/N ratio against each control factor. This indicates the optimum combination of control factor levels. If this corresponds to the design selected in step 4 then that is the overall best design among all the possible combinations of the selected control factor levels; go to step 8 (end of investigation). If not, then:
7. Create a new design based on the combination defined in step 6. That will be the overall best design (near-optimum); this can be verified by performing steps 2 and 3 for the new design, which will show that it has a S/N ratio higher than that of all other designs, including the one selected in step 4.
8. Stop.

5. DEFINITION OF PRINCIPAL DESIGN CHARACTERISTICS

5.1. Introduction to the Technical Design Framework

The first stage in the work programme has entailed the creation of the algorithm for the concept design shell. The algorithm has the capability of creating feasible technical designs and identifying and summarising the principal technical and commercial attributes of each design, allowing a selection based on these attributes to be made, see Fig.4.3.1.

The framework includes a suitable technical database for the development of conceptual designs, together with facilities for life-cycle costings. The shell incorporates the facility for investigations of areas such as resistance, seakeeping performance and structures when subject to parametric changes in say dimensions and speed. It is noted that several local-optimisation, sensitivity and uncertainty analyses have been undertaken and published, but few address the implications of integrating these into an overall practical design and decision making shell.

The concept design framework is structured in modular form, within a robust but flexible global shell, which will allow relevant additions and updates to be made to the data and local algorithms in a systematic manner. The modular approach also offers the opportunity for the insertion of user-defined data and the transport of data modules to other exploration models. Such an approach offers great flexibility, allowing the databases and design modules to be constantly updated to incorporate emerging statistical or experimental data and theoretical tools. This is important for a model aiming to cope with the rapidly developing fast ferry market.

The overall technical design approach is relatively conventional in form, with a design path including the primary constraint and checking features involved in evolving a feasible technical design. The shell includes modules on dimensions, powering, masses, seakeeping and costs (see Fig.4.3.1), which are described in detail in the following sections and in the next chapter.

The grouping of these modules, i.e. dimensions, powering and masses in this chapter and seakeeping and costs in the following chapter, is done for a reason. It follows the grouping of characteristics which is based on whether they are scenario-dependent or not. Dimensions, calm water performance and masses are characteristics which once calculated may be considered constant for each design and are not affected by the sensitivity analysis. On the other hand, seakeeping performance is dependent on the route and relevant environmental parameters while costs, both building and running, are dependent on economic parameters which are also varied during the sensitivity analysis. This affects the way these characteristics are addressed and justifies their discussion in a separate chapter. The present chapter deals with those characteristics which define a feasible technical design as an object or system irrespective of its probable performance in various alternative scenarios.

All these modules have been developed to an adequately operational level for the purposes of the overall model. However there is room for further improvement for some of the modules. Any limitations and possible future enhancements are discussed separately for each module in the respective sections.

5.2. Creation and Use of the Database of High-Speed Ferries

Published systematic data for the emerging ferry types such as the larger monohull craft, multihulls and hybrids are limited. It is thus necessary to establish a suitable database which is initially based on the limited existing historic data. The ever increasing number of fast ferries made possible the creation of a sufficiently sized database, lack of which would make any attempt of developing an algorithm as described above much more difficult, while at the same time the results would be subject to dispute.

The creation of the initial database resulted from an extensive literature search and has been constantly updated. The vast majority of data on existing fast ferries and newbuildings as well as proposed new designs is found in journals, mainly in [96], but also [97-98]. Its completion involved extensive measurements, calculations and manipulation of the available data. Some general comments concerning this database and its use are made in this section. A more detailed description of its creation and initial use is given in [99].

5.2.1. Structure of the Database

A large number of high-speed ferries are logged in the database. Most of them are already operating throughout the world, while some are at the stage of construction, or at least completed design. The vessels are divided in two major categories, passenger-only and vehicle/passenger carriers. The distinction between the two is necessary, because the latter would have an extra parameter influencing their size. Also, as they generally cover a different size range, the quantification of any factors or ratios and relevant formulae may be different.

A secondary distinction is made between monohulls and multihulls. This is necessary, not only because multihulls have a few extra dimensional parameters (e.g. hull beam, separation), but also because the analysis of the data would again lead to different quantification of the design procedure and possibly even to a completely different design path. A further distinction is made between different types of multihulls, i.e. foil-assisted catamarans, SESs, SWATHs, wave-piercers and 'standard' (conventional) catamarans but, as mentioned above, the available data at present is sufficient for the study of conventional catamarans only.
Four separate databases were therefore created, namely for passenger-only monohulls (coded as PM), passenger-only catamarans (PC), vehicle/passenger

monohulls (VM) and vehicle/passenger catamarans (VC). These databases are presented in Appendix A. It should also be noted that those concerning catamarans also include separately the other multihull types even though no algorithms have as yet been developed for them.

All the information found was included in the databases, namely dimensions, weights, capacities, speed, range, propulsive installations, and other additional information. Furthermore, ratios were derived in order to be used in the design procedure. A significant factor was the availability or not of general arrangement plans. For those vessels whose general arrangement plans were available, areas were measured and ratios calculated, as passenger and vehicle areas can have important influence in determining the size of each vessel. The number of vessels is adequate to allow reliable analysis of the relevant data.

The databases are considered to be of adequate size. The smallest one is that with passenger-only monohulls, which contains over 25 entries, while the other three are significantly richer. It must also be noted that in all cases there are several vessels that have been found more than once, but with slightly different characteristics, varying from one operator to the other. These variants are coded with additional indices (a, b, etc.) so that they can be distinguished and they have generally been treated as different vessels for most calculations. It was decided to include all such cases separately as the characteristics were considered different enough not to bias the database. The total number of vessels included in the databases, the updating of which continued until September 1998 within this research programme and will resume as part of ongoing research, is shown in Table 5.2.1. It can be seen that the total number of monohulls and catamarans is 270 and there are also 55 variants of other multihull configurations which are at present not investigated.

5.2.2. Analysis of the Data

The information included in the database was used to set up an initial design algorithm, the first step of which is the derivation of a set of main dimensions. As can be seen in Appendix A, the database includes a number of derived factors and ratios such as Froude number and hull ratios, for example L/B, B/T and $L/\nabla^{1/3}$ for the vessels with known displacement. For the vessels with available general arrangement plans for which areas were measured, the database includes additional area ratios. These were analysed as is described in the following section in order to investigate the implications of developing an area-based approach for the calculation of main dimensions. This comprehensive analysis led to the generation of a large amount of information; this can be seen in Appendix B, which includes data plots that were not used, and is discussed in detail in the following section.

The areas that appear in the database are defined as follows and summarised in the Nomenclature. A_S is the seating area, including corridors that are 'internal' in the seating areas, whereas A_P is the total area for use by the passengers, i.e. including toilets, bars/kiosks, duty-free shops, baggage spaces, lounges and other spaces accessible by the passengers. On the other hand, A_V is the vehicle area, including any empty spaces necessary for vehicle loading/unloading and turnaround. These areas are used for the derivation of ratios per passenger or per vehicle. It must be noted that the term 'vehicles' in this case means passenger cars, because a standard vehicle size must be used. The use of equivalent combined cars and trucks numbers would make the calculations more complicated without adding to their accuracy significantly.

A special comment must be made concerning the calculation of waterline length in the cases where it was not known. Waterline length is important among the vessel's dimensions, especially in the early stages, as it is used for the derivation of the other dimensions. For this reason, average values for the L_{OA}/L_{WL} ratio were calculated for each vessel category from the vessels for which both lengths were known, and these values were applied to the vessels whose waterline length was not available. In some cases the length between perpendiculars was known, and in these cases it was used as waterline length, because these two lengths are practically equal in the case of high-speed vessels which have transom sterns.

5.3. Estimation of Main Dimensions

The dimensions module entails the derivation of plausible dimensions based, in the first instance, on historic data. This provides only a starting point in the design process for estimates of preliminary dimensions which can then be updated at later design stages.

It was expected that capacities and speed would be the main parameters influencing the derivation of an initial set of main dimensions. This seems reasonable as carrying capacity directly affects the overall size of any ship while on the other hand speed affects hull coefficients and ratios. The use of these main parameters would also be desirable from a practical point of view as these, probably together with range, are more likely to be the basic requirements of a potential user of the model, i.e. a shipowner or operator.

However, extensive study of the available data revealed that passenger and vehicle capacities seem to be the only parameters influencing the derivation of an initial set of main dimensions. Speed, expressed by means of Froude number, did not significantly affect any of the main ratios (e.g. $L/\nabla^{1/3}$, B/T and L/B), as might have been expected. This may seem strange, but it can be clearly demonstrated by data plots of these and other ratios against Froude number. Such plots, whose bad correlations rendered them unusable for the purposes of this project, are given in Appendix B, which includes a number of data graphs which were not used. In these plots it can be seen that for all four vessel categories hull ratios such as L/B, B/T and $L/\nabla^{1/3}$ show no correlation with Froude number, as demonstrated by the scatter.

Furthermore, from the analysis of the database it became clear that an area approach should be applied and this is described in this section. The adoption of such an approach seems reasonable, as ferries are largely area-driven vessels, i.e. it is their area requirements that influence their design most strongly. The initial intuitive decision to adopt an area-based approach was confirmed by the statistical analysis of the data in the database.

The design flowpath is shown in Figs. 5.3.1 and 5.3.2 for monohulls and catamarans respectively. The areas are as defined in the previous section. It should be noted that different formulae apply to passenger-only and vehicle/ passenger vessels, as well as to monohulls and catamarans. The form of the formulae is the same, but the numerical factors vary, see Table 5.3.1. The use of an $L \times B$ product rather than an L/B ratio for the calculation of beam was preferred because the latter does not correlate very well with either speed (F_n) or length. A very significant feature of this approach lies in the fact that it allows the use of areas as main parameters, as they influence the length-beam product very strongly.

Furthermore, the more complicated three-stage calculation of $L \times B$ from N_P (see Figs. 5.3.1 and 5.3.2) was preferred as it allowed more freedom in providing the vessel with the desired level of 'accommodation quality', in terms of areas provided to passengers. A_S is calculated as a function of passenger number N_P, but variations are possible within reasonable limits dictated by the existing data, allowing the designer to select the desired level of seating comfort. In the same way, variations are possible for the A_P/A_S ratio used for the calculation of A_P, allowing the designer to select the desired amount of additional spaces for use by passengers. Instead of the three-stage procedure used here ($N_P \rightarrow A_S \rightarrow A_P \rightarrow L_{WL} \times B$), a two-stage ($N_P \rightarrow A_P \rightarrow L_{WL} \times B$) or even a one-stage process ($N_P \rightarrow L_{WL} \times B$) could have been applied, see graphs in Appendix B. This would make the algorithm much simpler, but would not allow for variations from the default areas. It has therefore been decided to treat A_S/N_P and A_P/A_S as parameters which can vary for a systematic design generation.

The layout of the vessel relating to number of decks can also be selected. However, in all cases a significant majority of the existing vessels followed a standard layout, which is therefore used as a default (two decks for passenger-only vessels, three decks for passenger/vehicle vessels). Deviations from this default are possible through built-in factors. Depth does not appear in Figs. 5.3.1 and 5.3.2 or in Table 5.3.1. Although it has no significance for hydrodynamic performance calculations, it is an important parameter for hull mass estimates and stability calculations. It can be calculated as a linear function of B or L, an approach dictated by the available data in the database of existing fast ferries.

The calculation of displacement is at present based on an assumed value of $C_B = 0.40$. This is reasonably typical for fast ferries and it was found that the vessels included in the database whose displacement was known had a block coefficient of the order of 0.4. This value is therefore used for the calculations combined with length-displacement ratio $L/\nabla^{1/3}$ and beam-draught ratio B/T. These are therefore also seen as parameters which would vary during a systematic design generation process. It should be noted that these two parameters are also used in systematic resistance series which justifies their use in this algorithm. Together with the area ratios described earlier they collectively allow the derivation of a full set of main dimensions. This analysis led to the approach presented in Figs. 5.3.1 and 5.3.2.

As far as the additional dimensional parameters of catamarans are concerned, demihull beam B_H is used instead of overall beam B for the initial calculations. Hull separation S is used as an additional parameter in the form of an S/L ratio, varied within the range dictated by the data in the database. Overall beam is then simply derived as $B = S + B_H$.

The basic characteristic of the approach presented in Figs. 5.3.1 and 5.3.2 and briefly described in this section is that it includes areas in the set of main parameters driving the derivation of dimensions, which is desirable, as this is the case with ferries in reality. A further feature is that the adopted approach allows the required quality of accommodation to be taken into account at the very first stage of the design process through the three-stage procedure for the calculation of L^xB. This is believed to be important, because the changes in required areas are significant and can heavily influence the size of the vessel. Such decisions should therefore not be left until the later design stages.

The data and regression plots that were used are shown in Figs. 5.3.3 to 5.3.6. The equations are shown in Table 5.3.1. All the regression equations give very good correlations between predictors and responses (in most cases $R^2>0.9$). This means that the algorithm is reliable and its outcome can be considered to be a good initial set of dimensions to be used for the later stages of the design procedure. It must be kept in mind, however, that as the algorithm is based on data from existing vessels it may not be safe to use outside the limits of the database, as extrapolations may not be reliable. On the other hand, the trends are very clear and extrapolating within a reasonable range should not create any significant problems. It is thus proposed that the algorithm be used with caution outside the approximate limits of the database, which are summarised in Table 5.3.2. Table 5.3.3 includes some example confidence intervals for these regressions; these represent typical test cases, i.e. usual parameter combinations for real designs, covering most of the reasonable parameter ranges. It can be seen that in most cases these are reasonable and only in a few cases they are relatively ‘wide’, but this occurs only close to the limits of the parameter ranges, mostly near the lower limits. The overall results can therefore be considered satisfactory.

It must be stressed that the database can be constantly updated and expanded, as new vessels can be added to it at any time. This enhances the strength of the database and, in consequence, that of the algorithm. The numerical details of the various design steps can then, if required, be updated in order to correspond better to the trends dictated by the addition of new data, allowing the model to keep pace with new developments taking place in the marine industry.

The dimensions module is developed to a satisfactory level. By using the area and hull parameters discussed earlier it allows the investigation of combinations that adequately cover the available range of current-technology designs. In this way the use of such parameters eliminates any problems encountered with data of unsatisfactory scatter. In the cases where correlations are satisfactory, regression equations are used such as those included in Table 5.3.1, with facilities for any possible variations if required (e.g. number of decks). In Figs. 5.3.1 and 5.3.2 it can be seen where statistical analyses (regression equations, average ratios) or parameter variations are applied.

Four separate programs (for passenger monohulls, passenger catamarans, vehicle monohulls and vehicle catamarans) have been initially written for the calculation of dimensions. The calculation of dimensions has also been included in a spreadsheet which has been developed for the application of the overall model. This allows more efficient and rapid calculations of main dimensions within the systematic design generation algorithm described in Chapter 8; also the spreadsheet approach is more compatible with the philosophy of systematic design generation, which was not possible with the initial computer programs. For these reasons the computer programs were eventually abandoned and the calculations of main dimensions are performed using the spreadsheet. Information on this spreadsheet is given in Appendix F.

5.4. Powering Calculations

The development of a reliable database for power estimates is considered essential, particularly as alternative ship types are to be explored. Use is being made of existing standard series data where look-up tables are employed, together with regression algorithms where applicable. In order to readily interpolate and extrapolate the database for exploration purposes, theoretical and experimental techniques may be employed, such as those used successfully for fast monohull and multihull vessels [85-88].

5.4.1. Calm Water Resistance

Use is made of existing standard series data for monohulls and the module currently includes the data for the NPL Series [100], Series 64 [101] and Southampton Extended NPL (higher $L/\nabla^{1/3}$ values) [87] in monohull mode. These collectively provide a good coverage of parameters and offer the facility to investigate a reasonable range of fast monohull ferries. Systematic data for multihulls is limited. The module currently includes the catamaran series tested at Southampton [87] which offers one of the most comprehensive sets of data available (10 hulls and 4 hull separations for each). The extension of Series 64 to include catamarans is desirable because Series 64 offers a wider range of block coefficients and higher $L/\nabla^{1/3}$ ratios which may be more appropriate for some of the catamaran demihulls. In recent years some systematic data and tools for high-speed monohulls and catamarans of more varied hull forms have emerged, e.g. [102-108], which may be useful for future extensions.

Thin ship theory developed for multihulls with transom sterns [85-86], has been effectively validated against experimental results and, particularly for the derivation of suitable wave resistance interaction factors, can be used to provide more flexibility in the investigation of a wider range of hull parameters.

The main applicable parameters are B/T and $L/\nabla^{1/3}$. For multihulls, demihull beam B_H is used instead of B and the length-displacement ratio is that of a demihull, while S/L is an additional parameter. A default value of $C_B = 0.40$ is assumed, which is used in the NPL and Southampton series and is reasonably typical for fast ferries. A series of interpolations are performed for the calculation of C_R for the vessel's set of parameters, using C_R values read in from data files containing the series data. This approach tends to be more accurate than using regression equations, and is preferred for parametric and comparative studies. Limited extrapolations are used to calculate C_R values outside the limits of the data files. This practice is considered satisfactory on account of the well ordered curves at high Froude numbers and supporting estimates by thin ship theory. Following standard practice, C_F is calculated from R_n using the ITTC correlation line. Wetted surface is calculated through a wetted surface coefficient C_S, which is derived from B/T and C_B using regression formulae provided for each series.

The naked hull resistance calculated from the series is then increased to include appendage drag. This is currently carried out by applying a percentage increase to the naked hull resistance. This increase applies only in the case when conventional propellers are used as propulsors and does not apply when waterjets are used. Effective power P_E is calculated directly as $R_T \times V_S$.

The resistance sub-module has been developed to a satisfactory level. Aspects to be further considered include the extension of Series 64 to run in catamaran mode, currently under way [109], as well as other possible extensions, e.g. offering the capability to perform calculations for alternative hull forms in addition to the round bilge ones.

5.4.2. Propulsion

An overall propulsive efficiency is calculated, leading to an estimate of the required installed power. This can be performed both for waterjets and conventional propellers with rudders so that comparisons can be made and the best solution selected.

In the case of waterjets, overall efficiency is currently estimated from available statistical data [110-111], as a function of speed. This is shown in Fig.5.4.1 and an approximate relationship that was found to best fit the data is as follows:

$$\eta_D = \frac{1}{1 + \left(\frac{16.8}{V_s[kn]} \right)} \qquad (3.2.1)$$

For conventional propellers, a standard optimisation procedure is used for an estimate of optimum open water efficiency η_0. Both commonly used propeller series, namely the Wageningen-B series [112] and the Gawn-Burrill series, are used for the calculation of open water efficiency. K_T and K_Q are calculated as functions of blade area ratio A_E/A_0, propeller diameter D (initially set to 0.6T), blade number Z and advance coefficient J, using regression equations which are similar for the two series. The corresponding pitch-diameter ratio P/D is calculated through the use of the Newton-Raphson iterative method. Hull efficiency η_H is calculated through thrust deduction and wake fraction, t and w_t, which in turn are calculated as functions of volumetric Froude number F_∇ using regression equations taken from [113] (t also varies with shaft angle α). Similar regressions also taken from the same reference are used for the calculation of relative rotative efficiency η_R. The overall efficiency $\eta_D = \eta_0 \eta_H \eta_R$ can then be established. This optimisation procedure is described in detail in [114].

Delivered power is calculated directly as $P_D = P_E/\eta_D$. Shafting and gearing losses are accounted for by a shaft efficiency η_S and a gearbox efficiency η_G. Both are given the typical value 0.97. Brake power P_B is calculated as $P_D/\eta_S\eta_G$. The required total installed power P is estimated assuming a margin for resistance increases due to hull roughness, fouling and weather. Resistance and propulsion calculations can be performed for any selected speed(s), allowing any desired operational speed to be investigated.

The propulsion part of the powering module has also been developed to a satisfactory level. Its strength would be improved by enhancing the η_0 optimisation procedure, which is currently based on user-input values for the main parameters, thus reducing the chances of obtaining a true optimum. Also it would be worthwhile to develop an algorithm for a more complete comparison between propellers and waterjets, taking into account aspects such as costs and weights in addition to efficiencies. For example, some literature exists on issues related to waterjet installations for fast ferries as well as on the implications of alternative propulsors for such craft, e.g. [115-118], and would provide some useful information for addressing this issue.

Two computer programs have been written to perform the powering calculations, one for monohulls and one for catamarans. Each one of these programs incorporates routines for resistance calculations for the various systematic series together with routines for propulsion calculations. It would be possible to integrate these into one program, which in turn may form part (as a subroutine) of a final global program. At the moment all the computer programs that have been written, including codes concerning powering calculations and mass and costing estimates, are independent of each other. Integrating these into one global program could be performed in the future, provided that each individual module is satisfactorily developed to a fully operational level. Some information on these programs is given in Appendix F together with full program listings.

5.5. Estimation of Masses

An accurate mass estimate is important for high-speed vessels, where relatively small changes can have a significant effect on vessel performance. At the same time, a literature survey indicates that published data for existing built vessels is sparse. The total light ship mass is divided in the classical way into hull, outfit and machinery masses.

5.5.1. Hull Mass

An equipment numeral (E) approach [18], or alternatively a cubic number (LBD) approach, based on a limited number of basis ships and aluminium alloy as the construction material, can be used for an approximate first estimate of the hull mass. The potential and implications of these approaches have been investigated and it has been decided to develop a variation of the former that would be suitable for high-speed craft. Such an approach has been investigated in [119] and is currently being further developed as part of continuing research on the subject. Some results from initial parametric investigations are shown in Fig.5.5.1.

Parametric studies are applied to the rules of classification societies, together with more fundamental approaches based on suitable applied structural loadings. A realistic hull mass estimate can be performed in this way, using the midship section method. Such approaches are well documented, e.g. [94], [120-121]. A midship section is designed and scantlings are calculated according to alternative classification society rules for high-speed light craft, see [122-124], and an average mass per unit length is derived. This is then applied to the vessel's length, taking into account longitudinal distribution and special considerations for bow (slamming), stern (machinery-induced loading) and superstructures. These parametric studies are enhanced by data on existing vessels allowing a validation and calibration of the results. This leads to the development of an equipment numeral approach specifically designed to cope with high-speed craft.

Finally, although aluminium alloy is considered to be the construction material in this study, future studies could investigate the potential of other alternatives, such as composite materials for smaller vessels [125-126].

5.5.2. Machinery Mass

A database of machinery masses has been assembled. This pays attention to developments in, and applications of, prime movers and propulsors suitable for high-speed craft. Machinery mass can be calculated with some accuracy from these data, as the masses of the main engineering components, namely engines, gearboxes and propulsors, which represent the largest part of machinery mass, can be calculated reliably.

The database is adequately sized and includes diesel engines (medium- and high-speed), gas turbines, gearboxes and waterjets [127-128]. Clear trends are observed in the data, allowing the calculation of the weights of these components, see Figs. 5.5.2 to 5.5.5. Table 5.5.1 summarises the equations used for these calculations, i.e. the ones that were found to fit the data best. In the case of diesel engines, as expected, mass is dependent on power/speed ratio rather than power (see Fig.5.5.2). This indicates that the addition of a local-optimisation algorithm with engine speed as the parameter would be a useful future enhancement of the module. The available range of speeds could then be investigated and the optimum selected on grounds of mass (favourable to high-speed diesels), fuel consumption (favourable to medium-speed diesels) and life-cycle costs.

Developments in machinery, most notably main propulsors, for high-speed ferries are taking place at increasing frequency. It is therefore important that the database be frequently updated and the equations requantified if necessary in order to keep pace with these developments. The selection of prime movers is also a very important matter that needs to be addressed with caution, taking into account the different operational requirements and any practical implications of using various alternatives in each case [129-131]. These have been investigated and are discussed in [132] which also provides further engine data.

The remaining part of the machinery mass, including generators, pumps, piping and other auxiliary equipment, can be calculated as a function of installed power. At the initial stage of the design process the application of a simple factor on main machinery mass may be sufficient. The potential of this approach is being investigated.

5.5.3. Outfit Mass

For a preliminary estimate of outfit mass, statistical data and factors derived from existing ferries are applied. These allow an initial estimate to be made based on total passenger and vehicle areas. The most significant component of outfit mass is accommodation weight. This can be initially estimated using a mass per unit area, and includes lounges, dining rooms, self service areas, air type seats, receptions, foyers, corridors, galleys, toilets and any cabins. Typical values are in the region of 80-100 kg/m^2, depending on the desired accommodation quality. The remaining mass, including additional equipment not included in the machinery mass, is initially estimated on the basis of LBD (B_H for multihulls).

5.5.4. Deadweight

Accurate deadweight calculations can be performed once the main operational requirements of the vessel are defined, namely speed, range and capacity. Standard values for weight per person (75 kg), passenger or crew, luggage (30 kg) or effects (60 kg), and per vehicle (1.0 t) are applied, allowing a direct calculation of the vessel's payload. Water and provisions weights are calculated using typical daily consumption per passenger values (20 + 10 kg). The database of high-speed ferries includes detailed deadweight breakdowns for several vessels, which are used to confirm and calibrate these calculations. Fuel and lubricating oil weights are calculated through installed power, consumption and range, including a suitable margin for arrival condition.

5.5.5. Summary

The masses module comprises four separate parts that are developed to different levels and therefore require further work to different extents. In general, further work needed concerns: the finalisation of a cubic number approach for the calculation of the 'remaining' outfit mass, i.e. excluding the accommodation weight which is being calculated through statistical factors; the development of a local-optimisation algorithm for diesel engine speed, allowing the main machinery mass to be calculated with greater flexibility when diesel engines are installed; and the definition of factors for the calculation of total machinery mass as a function of the mass of the main machinery components. Appendix F includes a listing and some information on the relevant computer program.

5.6. Other Features

It is desirable that as a minimum a basic stability check facility be included in the model, at least for screening purposes. Such a stability module will firstly act as a fundamental screening device to check on adequate intact stability for the evolution of a feasible design. The monohull check establishes a GM using empirical relationships for KB, BM and KG. The multihull normally presents no problems with initial stability, although excess stability results in uncomfortable motions and is an area which is incorporated in the seakeeping assessment.

Additional facilities are aimed to be included within the technical design framework which will address the aspects of manoeuvring, safety/reliability and environmental issues. The importance of such issues is constantly increasing, e.g. [133-135], and the development and inclusion in the model of such modules would be desirable and will form part of continuing research on the subject.

The development of criteria for manoeuvring is considered desirable as a means of assessing operational abilities, such as coursekeeping and low speed manoeuvring, and safety. Work on this issue is under way at the University of Southampton which when developed will be included in the overall model.

Safety aspects can be pursued by establishing relative levels or criteria of safety, as well as screening for prescribed minimum standards. These ought to be investigated for the vessel types under consideration using attributes such as damaged stability, manoeuvrability and control characteristics and systems redundancy.

Environmental issues emanating from technical attributes such as speed, fuel economy, pollution, noise and low wash ought to be collated and assessed for each vessel type. These issues are receiving increased attention in recent years, both from regulatory bodies and from the general public as well, and they are gradually affecting the design of high-speed craft.

5.7. Example Calculations

Example designs which have been generated by applying the methodologies discussed in the last two chapters are presented in order to demonstrate their use. Comparison of these vessels with existing high-speed ferries indicates that the algorithms presented generate realistic and feasible designs. Two major cases are examined separately, namely passenger-only and vehicle/passenger vessels, which allows the generation of both small and large vessels to be demonstrated. For each of these two categories monohull and catamaran designs are generated, illustrating the use of the algorithms for these two major vessel categories.

For the case of passenger-only vessels the assumed requirements for the developed designs are to be able to carry 350 passengers at a service speed of 33 knots. Based on these requirements, an initial set of main dimensions can be calculated as discussed in section 5.3. Table 5.7.1 includes the values of the design parameters used for the calculations in this case study, both for the monohull and the catamaran. The derived sets of dimensions are shown in Table 5.7.2 for the two vessels. Table 5.7.2 also includes a powering estimate for each vessel based on the methods and data sources outlined in section 5.4. These powering estimates include a 15% rough weather margin. The generated designs compare well with existing high-speed ferries of similar carrying capacity and speed. Such are, for example, monohulls PM 6, 10 and 26 and catamarans PC 4, 8, 10, 12, 17, 20, 29, 30, 33, 36, 43, 46, 54, 56 and 61, which can be seen in the database in Appendix A for a direct comparison.

In a similar manner to the previous case, for the vehicle/passenger vessels the assumed requirements include carrying capacity and speed, set here to 620 passengers and 160 cars at a service speed of 36 knots. The parameter values and derived sets of dimensions, including powering estimates, are given in Tables 5.7.3 and 5.7.4 respectively for both the monohull and the catamaran. The data sources for the powering calculations were as for the previous examples. The generated designs compare well with existing vessels of similar carrying capacity and speed, as was the case with the passenger-only vessels. Real ships that can be used for comparison are monohulls VM 3, 6, 10, 16, 33, 36, 38 and 41 and catamarans VC 3, 21, 23, 40, 53 and 54, which can all be found in the database in Appendix A.

The only major observation that needs to be made concerns the fact that the vehicle/passenger monohull comes out slightly overpowered, which is attributable to the limitations in the existing systematic resistance series, which impose the generation of monohulls that are too 'full'.

6. DEFINITION OF SCENARIO-DEPENDENT PERFORMANCE CHARACTERISTICS

6.1. Seakeeping Performance Calculations

Seakeeping performance attributes including motions, passenger comfort, structural integrity, speed loss and operational limits can have a significant influence on the choice between competing vessel types for a particular route. The assessment of seakeeping requires a knowledge of the motion transfer functions for the particular vessel or variant under consideration and an assumed wave energy spectrum for the relevant sea area. Spectral calculations can then be used to determine the motion energy spectrum and, from it, statistical quantities or attributes such as the RMS values of the various motions and the probability of an individual motion exceeding a given value. Because of the significance of these issues, it is important to investigate and incorporate them as comprehensively as possible into the early design stages [136-137].

Methods of condensing the seakeeping attributes into a single criterion such as that proposed by Bales [60] have been explored. The more specialist nature of the fast ferries under consideration suggests that the attributes should be retained in their individual forms. In this way the output can be more transparent, offering increased flexibility in determining an appropriate approach for an overall evaluation of competing designs. At present, the method used considers the RMS values of the various responses in terms of the probability of the motions or accelerations not exceeding a certain value. This in turn indicates the operational limits or availability of each vessel due to each particular response. The model allows the choice of alternative sea spectra together with the facility to input various maximum exceedance levels. A more detailed description of this methodology is given in [138].

Systematic data describing the transfer functions are required if variations of a particular vessel type, and comparisons between vessel types, are being considered. Some experimental data for high-speed craft have emerged in recent years, e.g. [139-144]. However, they are still limited and extensions to such data are usually achieved using theoretical means. In the present work, for monohulls and catamarans, recourse is made initially to the systematic data in [92]. These data offer comprehensive information allowing seakeeping calculations to be performed within a certain range of parameters. This in turn allows the overall methodology to be set up and validated. These systematic data will be extended using the results of ongoing experimental and theoretical work which is under way at the University of Southampton. This includes, for example, experimental work on multihulls in oblique and irregular seas [145] and the development of theoretical methods which have shown promising results for higher speed craft [89-91]. The addition of such data will represent a useful enhancement of the module allowing it to overcome the limitations of the range of data included in [92].

The quantification of seakeeping performance and creation of relevant attributes to be used for comparative evaluations is not a straightforward task. Diverse aspects such as structural loadings, operational implications (speed/powering) and passenger comfort are affected and all need to be taken into account. The implications of addressing these issues within the context of the decision making framework are of utmost importance and are discussed in detail in the following Chapter 7.

The seakeeping module is considered as acceptable for establishing the overall methodology. It has been developed to a level that allows calculations to be performed to a satisfactory level for the needs of setting up and testing the overall decision making algorithm. These results are reliable for monohulls and catamarans which are covered by the available range of systematic data. These are briefly presented in Appendix G together with the systematic data used for powering calculations as discussed in the previous chapter. The scope of the module is however currently confined to this set of specific values of the main parameters, which do not always cover the required range of vessels, making interpolations or extrapolations necessary. Further work is therefore in progress as discussed earlier in this section, including also further extensions to the database by generating data for catamarans of Series 64 hull forms [146]. The existing program was developed as part of earlier research [89] and is therefore independent from the other codes which have been written as part of this research programme. The same comments concerning possible future integration into a global program therefore apply as for the dimensions, powering and masses modules.

6.2. Estimation of Costs

Life-cycle costs, including both building and running costs, are among the most important parameters influencing the choice between competing vessels. Building costs are generally high for high-speed ferries, as a result of a number of factors relevant to the advanced technology involved, such as the use of aluminium alloy as the main hull construction material, the requirement for high installed power to achieve higher speeds and the possible installation of advanced ride control systems for improved seakeeping performance. Running costs are also high, mainly because of the high installed power, which leads to increased consumption of expensive light fuel.

On the other hand, revenue can also be expected to be high, due to the transportation of large numbers of passengers and vehicles, which is made possible by the higher speeds, leading to larger numbers of trips. Furthermore, higher fares may be charged, compared with conventional ferries. The required fares, which may be among the parameters heavily influencing the attractiveness of each vessel, can be calculated once the operational profile and the costing attributes of the vessel are known.

For these reasons, estimates of costs with a good level of accuracy are desirable at the initial stages of the design process. This may not be easy, as costing data necessary for the calculations are usually not readily available. A brief discussion of possible ways of addressing this subject is presented in this section.

6.2.1. Building Cost

Building cost is normally divided into hull, outfit and machinery costs. A further division is carried out for these three components into material and labour. For these estimates, detailed data is required from shipyards, or machinery manufacturers for the relevant acquisition costs. Such data are not normally freely available from shipyards.

A simpler but more approximate approach that can be used considers total costs per 'worked' tonne of aluminium alloy or outfitting mass, including material and labour. These are easier to estimate and assemble at the stage of conceptual design, based on past experience. Similarly, for machinery costs (plus auxiliary equipment and systems) total amounts may be estimated, but input from manufacturers is still necessary. An alternative would be to use approximate empirical equations, which may however not be sensitive enough for machinery installations of advanced high-speed vessels.

A database is being developed along the lines of that described, but in order to overcome current deficiencies in the availability of detailed data, the implications of using even simpler approaches were investigated. These involve the estimation of total building cost directly as a function of one or more of the vessel's principal attributes. Such an approach is inevitably based on experience only, as it uses actual contract prices for built vessels for the derivation of regression equations [96-98]. It may also be considered too simplistic, but the results obtained prove to be reasonably accurate over a wide range of existing high-speed ferries. It is therefore believed that such an approach can be used for an initial estimate of building cost, which can later be revised when more detailed information is available.

Initially, single parameter regressions were investigated, allowing the derivation of building cost from attributes such as deadweight or installed power. The best results were obtained with length, which is known to influence heavily the building cost of a vessel. Excellent correlations ($R^2=0.97$ in all cases) were observed for conventional catamarans and monohulls, which are the main vessel types currently being investigated, as well as for semi-SWATH catamarans, see Figs. 6.2.1 to 6.2.3.

Moving on to multiparameter regressions, it was considered that these should be based on the actual basic requirements of the vessel, namely passenger and vehicle capacities and speed. Promising results were obtained for all three vessel types, see Fig.6.2.4. Some problems were encountered with smaller vessels, as can be seen in Fig.6.2.4 and Table 6.2.1. Equations 6.2.1-6.2.3 should therefore be used with caution at the lower end of the size range. The derived regressions for building costs of catamarans, monohulls and semi-SWATHs are given in the following Equations 6.2.1 to 6.2.3.

$$C_C[\text{M \$US}] = -18.4 + 0.0294\ N_P + 0.111\ N_V + 0.445\ V[\text{kn}] \quad \{R^2=0.89\} \quad (6.2.1)$$

$$C_M[\text{M \$US}] = -37.6 + 0.0115\ N_P + 0.121\ N_V + 1.230\ V[\text{kn}] \quad \{R^2=0.96\} \quad (6.2.2)$$

$$C_S[\text{M \$US}] = -30.9 + 0.0465\ N_P + .0675\ N_V + 0.841\ V[\text{kn}] \quad \{R^2=0.99\} \quad (6.2.3)$$

This approach may be considered oversimplified, but it does provide an easily applicable alternative for a reasonable initial estimate of the vessel's building cost at the initial stage of the design process, when detailed data may not be available and the application of more accurate calculations is not possible. The results are reasonably reliable for vessels of current technology the construction of which does not involve any implications that differentiate them from the existing monohulls and multihulls included in the regressions. It should of course be used with caution, although it gives satisfactory results for a wide range of high-speed ferries. Some example confidence intervals for these regression equations are given in Table 6.2.1. It can be seen that the results do not seem to be very satisfactory, at least for 95% confidence. The problems are more important for parameter values at the lower end of the range where the 95% confidence intervals are clearly too 'wide'. These problems are of course due to the small size of the available sample which affects the relevant C.I. calculations. It is believed that the addition of more vessels in the sample would broadly confirm the existing regressions and at the same time would improve the confidence results. In any case the obtained 'mean' values do provide a reasonable initial estimate, but the poor confidence results indicate that the development of the more detailed approach would be useful.

Work does therefore still continue on developing the detailed approach, as this will provide a better facility for assessing the implications of particular design changes and will help reveal the effects of specific parameter variations. Hull material and main engine installations can then be seen as design parameters with distinct and easily identifiable effects on masses and costs and thus on the performance attributes of each vessel. This is better suited to the philosophy and the needs of the overall design and decision making model which involves the systematic generation of alternative designs. For the initial development of this approach the overall regressions presented earlier can be used for the calibration of the model. As algorithms are developed for the calculations of the various building cost components, the total building cost results provided by the regressions can be used for a comparison and check indicating the reliability of the results obtained by the separate parametric calculations.

For these detailed calculations the usual division of building cost into hull, machinery and outfitting costs is followed. These three major components are considered separately. Outfitting cost is the most difficult to estimate at the concept design stage as it involves numerous accessories and auxiliary machinery components which cannot be known at such an early stage. Calculations of outfitting cost are easier to perform at a later preliminary design stage.

Hull cost can be calculated reliably if data on material and labour costs are available from shipyards or any other source. As mentioned earlier, total costs per 'worked' tonne can also be used allowing the calculations to be performed directly without compromising their accuracy and the reliability of the results. Such information needs to be provided by shipyards as well. Some such data are available and are under investigation as part of ongoing work on the subject. These must be used with caution as they may be outdated or applicable to different vessel types and construction materials. Aluminium alloys are seen as the primary construction materials within this study, but it would be desirable to be able to investigate other alternatives, such as high-tensile steel for larger vessels for example or combinations of steel hulls and aluminium superstructures.

The algorithm for machinery cost calculations has been developed to a more advanced level. Comprehensive data have been assembled as part of an investigation into alternative machinery installations for high-speed craft [132]. These include initial costs for several main machinery components suitable for such craft, such as high-speed diesels, gas turbines, waterjets and suitable gearboxes. Analysis of these databases has allowed the development of algorithms for the calculations of the costs of such components which represent the largest part of machinery cost. These are based mostly on installed power and they can be seen in Figs. 6.2.5 to 6.2.8 and in Table 6.2.2.

6.2.2. Running Cost

Running costs can be readily estimated if detailed information on the vessel's operating profile is available. However, this will not always be the case at the stage of concept design. Effort must be put into attempting to calculate accurately as many of the components of running cost as possible with the available data. This is desirable because, even though full operational simulations may not be preferred by operators, representative detailed simulations may still be necessary in order to determine the relative importance of the various components. This in turn would, for example, allow the selection of the components to be included in a limited set of primary attributes to be used for the comparison between competing designs. These are explained further in Chapter 7.

The various components of running cost are divided into two main categories. The first includes those costs that occur only when the vessel actually operates and therefore increase with increased vessel operation. These are highly dependent on the route and the vessel's operating profile. The second category includes costs that are constant, regardless of whether the vessel operates or not. Some of these can be independent of the route on which the vessel operates but highly dependent on the vessel's building cost.

For the calculation of operating costs, the main characteristics of the vessel's operation must be defined. These include distance(s) and operating speed(s), taking into account any port or sheltered water restrictions, manoeuvring time and turnaround time, which collectively allow the determining of the number of crossings per day. Such information will be readily available if the route on which the vessel is to operate is known. If the vessel is not designed to be route-specific, some basic assumptions will have to be made.

Specific fuel consumption at each speed is used to calculate daily fuel consumptions. The effect of reduced power operation (manoeuvring, port restrictions, etc.) should not be neglected, due to the increase in specific fuel consumption, especially if gas turbines are used. These calculations also account for auxiliary fuel and lubricating oil consumption. Fuel costs are directly derived by using the appropriate fuel and oil prices.

Machinery maintenance cost is normally calculated directly using a standard cost per operating hour. This is fairly constant between similar engine types, but is significantly lower for gas turbines compared with diesel engines. This simple approach is adequately accurate and is actually being widely used, allowing the avoidance of unnecessary complications in the cost estimation process. The cost of hull maintenance is neglected, as it is low and does not affect the overall results.

Port charges can be significant yet at the same time difficult to model. They tend to be high in the case of high-speed ferries, because of the large number of daily crossings. Actual charges per call will obviously vary from one port to the other, but in any case they depend on the size of the vessel. Preliminary investigations indicate that quoted charges can be very high and may even lead to total expenses significantly higher than fuel cost. However, this may not be the case in reality and operators will often make special arrangements with port authorities, leading to major reductions in charges actually being paid. This situation makes the calculation of port charges difficult to model. At present, the model uses a proportion of the quoted charges and the facility exists to carry out parametric studies to investigate the effect of varying port charges on the total running cost of the vessel.

These costs are calculated on a daily basis. Yearly sums are then derived using the number of operating days per year. At this stage the effect of lost voyages due to weather, leading to reduced operating costs but most importantly to reduced income, is not taken into account. This is carried out at the stage of decision making, when seakeeping attributes are quantified and evaluated, allowing the vessel's availability to be defined. After the vessel's operating costs have been calculated, the remaining annual costs are added.

Crew costs are calculated directly using the required crew size, breakdown, and relevant wages. Average wage rates will decrease with increasing passenger capacity, because most of the additional crew members will be at the lower end of the wage range. A default value is used for administration cost, as this does not vary significantly with vessel size or capacity. Annual insurance expenses are calculated directly as a percentage of the vessel's building cost, typically 1.5-2%, although even higher values can occur in less developed markets where the introduction of high-speed ferries may be considered a risk. A small amount may also be added to account for third party liability, which is a function of crew number.

Capital cost is normally the most significant component of running cost, due to factors such as high initial cost, short economic life and possible high required opportunity interest rate to account for high risk investment in unproven designs. Capital costs are calculated through a capital recovery factor (CRF), modified to account for taxation, and using typical values of 10% interest rate over 10 years, including 50% taxation.

6.2.3. Summary

Simple computer codes for initial investigations have been written for this module. Information on the computer programs which have been written to allow these initial investigations to be carried out is given in Appendix F together with full program listings.

As for further work, certain actions need to be taken in order to facilitate a more detailed calculation of building costs. Data for costs per 'worked' tonne or more detailed separate data for material and labour cost per tonne must be assembled and validated for hull structure. More precise calculations will be possible as the more detailed model for mass estimates is developed, allowing accurate hull mass estimates which can be used for reliable building cost estimates.

7. DECISION MAKING SET-UP

7.1. Introduction to the Decision Making Framework

After the main characteristics are defined for each alternative design as described in Chapter 5, performance attributes must be properly quantified in order to allow the comparison, ranking and final selection between the competing designs. This includes the calculations described in Chapter 6 for seakeeping and costing characteristics. However, the accurate definition of a set of attributes which adequately describe the performance of each vessel as well as the creation of a sensitivity analysis methodology need to be performed first. These are discussed in this chapter while Chapter 8 offers a detailed description of the practical application of the model.

In Chapters 3 and 4 the main requirements for the developed approach have been discussed in detail. In addition, the model must be transparent in the sense that it should allow potential users to identify the attributes, goals and criteria on which the decision has been based. It is people who make final decisions at the end of the day and this should be kept in mind. These aspects have indicated that the framework should be developed using a 'primary attribute' approach; this is based on the selection of a limited set of attributes considered to be the ones that affect the comparison (and therefore the selection) between competing designs.

The decision making process in the case of ferries becomes more complicated for the reasons discussed earlier in this thesis. These include the concept of passenger satisfaction or preferences. Effort must therefore be put in an attempt to quantify this concept and integrate it into the decision making process. The humanistic nature of this problem suggests that the use of fuzzy sets seems to be a good approach. Fuzzy sets represent a powerful tool for addressing such humanistic problems, and particularly for quantifying natural language terms, which is exactly the present problem.

The ability to quantify natural language terms actually proves useful in a much broader context. Apart from the subjective attributes concerning passenger satisfaction, objective and quantifiable technical or economic attributes also involve natural language terms, such as 'cheap', 'good', 'low' or 'roughly', 'not much greater than' and so on. These may create the same problems in their quantification, fuzzy sets are therefore used across the overall decision making process, allowing uniform modelling of all primary attributes.

As a result it can be said that the following major initial goals can be defined for the setting up of the overall decision making framework: (a) to define a (limited) set of primary attributes on which the comparison/selection will be based - subjective preferences concerning the attractiveness of each vessel should be quantified in some way and included in this set; (b) to use fuzzy sets in order to address the above-mentioned issues, i.e. appropriate membership functions should be defined in each case; and (c) to generate the facility for comprehensive sensitivity analyses.

It is clear that the careful selection of appropriate attributes is of paramount importance. The very definition of such attributes is not straightforward and attention is required in order to create a set of attributes which will be realistic and comprehensive, and at the same time clearly defined and simple. The development of such a set of attributes is discussed in detail in the following section.

As priorities/weightings may be assigned only to a limited set of primary attributes, the selection of this set might affect the way in which these weightings will be defined. The same is true for the definition and application of appropriate fuzzy sets. In-depth investigations have been performed in order to provide some insight into the definition of fuzzy attributes and their membership functions. These are discussed in Section 7.3.

The importance of performing a reliable sensitivity analysis is paramount. To make this clear, one of the most important aspects of the overall framework needs to be clearly mentioned: attempting to perform overall optimisations, in the narrow way they are usually defined, is not desirable. These can be ill-defined in the first place, and (probably even more importantly) they are far from being realistic, in the sense of successfully simulating the actual decision making situations in the fast ferry market. Being realistic in that sense is one of the major goals of the project.

What is preferable is the derivation of a set of satisficing solutions, without attempting to strictly define an optimum among them. These solutions can be compared/ranked based not only on their average performance, but also, and probably even more importantly, on their 'robustness', i.e. their ability to maintain their performance as much as possible when various parameters affecting it change for any reason. This is of utmost importance and a top priority in reality in the fast ferry market, where a design needs to be robust in order to be successful, as it needs to be able to operate profitably if the conditions, economic or other, vary (which they do). With all this in mind, the importance of a reliable sensitivity analysis, which is the subject of the concluding section of this chapter, is evident.

A number of preliminary representative investigations were carried out to highlight problems arising in the decision making process. These studies indicated that a primary attribute approach is both plausible and practical, providing the opportunity of a direct comparison between the selected attributes of competing designs. The results however also showed that differences between alternatives can be marginal and might lead to erroneous decisions. This highlights the importance of establishing a sensitivity analysis mechanism as part of the overall model. It was also seen that the selection of the set of attributes on which to base the comparison affects strongly the final outcome. The implications of seakeeping performance attributes and their quantification became apparent as well. All these aspects were therefore identified as significant issues to be addressed within this framework and they are discussed in the following sections.

7.2. Selection of Primary Attributes

The definition of the set of primary attributes to be used for the ranking of competing designs is based on operational requirements. It is believed that in this way the overall framework will be more realistic and useful, meeting the requirements of the fast ferry market. The final selection of primary attributes as well as the reasoning behind it are briefly discussed here. The comparative nature of the framework should be clearly pointed out. This affects strongly the selection of primary attributes, which depends not only on their relative importance, but also on the extent to which they may vary between competing designs. For example, no matter how important an attribute may seem, if it is similar for all competing designs it loses effective significance for the comparison/ranking and final choice.

The selection of primary attributes is schematically shown in Fig.7.2.2. It is based on the fundamental requirement for a high-speed ferry, which is commercial success, or profitability. In order to achieve this the two major goals are to minimise the outgoings and maximise the income. The latter is considered to be partly achievable through passenger satisfaction, which would ensure high utilisation for the vessel and might also allow higher fares to be charged. This approach leads to the definition of a set of six basic characteristics a design is required to possess in order to be considered satisfactory: (1) low initial investment; (2) low running expenses; (3) high accommodation quality; (4) good seakeeping performance (ride quality); (5) high operational reliability; and (6) high 'attractiveness'. The first two directly result in low outgoings while the remaining four lead to passenger satisfaction and more generally to high income, see Fig.7.2.2.

The next step is the definition and selection of a set of attributes that will comprehensively describe the performance of each design in the context of these requirements. Although comprehensive, following the fundamental reasoning of the proposed approach this set should at the same time consist of attributes that are relatively simple to define, calculate and interpret. This is not easy in all cases.

7.2.1. Seakeeping-Related Attributes

Operational reliability is seen as dependent on weather limitations (machinery reliability can be considered similar between competing designs). This implies that reliability is influenced by seakeeping performance and therefore these two aspects are investigated together.

As with the overall framework, the selection of the seakeeping attributes, which are of great importance for passenger ferries, is also based on operational requirements. Initial investigations indicated that no less than three such attributes would be necessary to provide comprehensive information about each vessel's performance. Attributes considered initially included motion sickness incidence, speed loss in waves and operational availability.

Speed loss was seen as involuntary, i.e. dependent on powering limitations, as opposed to voluntary, i.e. deliberately imposed for reasons of passenger comfort. However, one of the major operational requirements is that the defined operating speed is considered to be strictly maintained in any case, i.e. speed reductions are generally unacceptable (apart from any compulsory ones due to port or sheltered area restrictions). This is consistent with views expressed by operators, who tend to operate their vessels on a run or cancel approach, cancellation being based on passenger discomfort levels (loss of future custom), as well as on purely regulatory, naval architectural or readily calculable commercial reasons. Local sea states and wind directions may be the deciding factors in such cancellations. In other words, cancellation rather than passenger discomfort, slow speed or delays tends to be preferred in order to maintain overall passenger satisfaction. Speed loss was therefore seen as inappropriate as an attribute and power increase required in order to maintain the defined operating speed is used instead. This is an easily quantifiable attribute which also affects fuel cost directly. If required, however, speed loss can relatively easily be re-introduced as an attribute in place of power increase if this better suits the needs of a particular application or the preferences of a particular user.

There is a need to establish a criterion for the probability of loss of journey based on some minimum level of passenger comfort. A first assumption at quantifying a level of passenger comfort can simply consider the probability of exceeding certain limits of ship motions and accelerations, although these limits need to be defined. This would be similar to establishing the operational limitations of the vessel due to bad weather and, as a first approach, simply considers the relative levels of exceedance between competing designs.

The definition of the three seakeeping attributes is schematically shown in Fig.7.2.1. The attributes selected finally are defined as follows. The analysis assumes operation on specified routes, which means that the environment in each scenario is known (wind and wave data). The operating profile is also considered to be defined (known), which is necessary for the relevant calculations.

- Motion sickness incidence is defined at the given operating speed and at weather conditions, say 'A', which are seen as critical for any reason, or are those that are expected to be encountered most frequently. Weather conditions can include sea state (wave height and period) and wind/wave direction.
- Power increase (for maintaining the defined operating speed) is defined at weather conditions, say 'B', which are critical, close to the operational limits of the vessels, therefore probably more severe than 'A'.
- Availability is defined by the operational limits for each vessel. These are derived from weather statistical data for the route, required operating profile and given exceedance limits for motions and accelerations, indicated by international rules and standards, e.g. [147-148]. This directly indicates the likely percentage of the year when each vessel would normally be able to operate.

It is not always clear whether conditions 'A' and 'B' should be different or not. That would depend on the definition of 'A', i.e. 'critical' or 'most common', see Fig.7.2.1. In the former case they might be the same whereas in the latter case that would be unlikely. Choosing the latter case seems to make more sense, unless the sea in the route under investigation is considered to be mostly calm and no problems would be expected for most of the time.

Overall, it can be said that motion sickness incidence indicates the ride quality for most of the operating time of each vessel and availability covers the aspect of operational reliability; power increase, although dependent on seakeeping performance and related to operational reliability, is also directly connected with fuel cost.

7.2.2. Other Attributes

An obvious selected attribute is building cost, which to a great extent defines the level of the initial investment. It also heavily affects running expenses (capital cost may be the largest component of running cost) and it is therefore thought to be one of the most important attributes. Another selected attribute is annual fuel cost. Not only does it form a significant part of total operating cost, but it may also vary greatly among competing designs, unlike other running cost components.

Moving on from techno-economic attributes to those directly affecting passenger satisfaction, the problem becomes more complicated. Accommodation quality directly affects passenger satisfaction but is a complex term comprising several aspects. It was decided to select total passenger area as the attribute used to model this aspect. This is a simple approach, but total passenger area is an important factor and strongly influences the perception of overall quality of accommodation. Other factors which are difficult to model or quantify are taken into account within the overall 'attractiveness' attribute.

Defining an attribute to account for the concept of attractiveness is not easy. However such an attribute can be important for passenger ferries and effort must be put into its development. It is expected that some form of attractiveness index will be introduced, its definition and method of calculation however are under development. This attribute is intended to incorporate all the subjective passenger preferences and other aspects which determine the overall attractiveness of each vessel, whether for passengers or operators. These may include for example aesthetics, ergonomics, internal noise levels, environmental aspects (e.g. wash, external noise, pollution) and safety.

Following the analysis discussed earlier, the primary goals a vessel has to achieve in order to be considered satisfactory are set as: (i) low building cost; (ii) low annual fuel cost; (iii) large total passenger area; (iv) low motion sickness incidence; (v) low power increase in waves; (vi) high availability; and (vii) high attractiveness. This is shown in Fig.7.2.2 which presents schematically the selection of all seven primary attributes.

7.3. Quantification Using Fuzzy Sets

Fuzzy sets represent a most useful tool in quantifying and modelling the various attributes in the context of the present research programme. This is closely related to the problem of subjective attributes, concerning mainly passenger preferences, which are not easily quantifiable. Seakeeping, economic and other attributes may also fall in this category. The definition of membership functions for the fuzzy sets depends on the definition of these attributes.

It was decided to use fuzzy sets for all the primary attributes, even those that are clearly technical and directly quantifiable. This allows a uniform way of modelling the attributes, which is important for the derivation of an overall ranking and selection. In that way the membership functions may be seen in essence as similar to utility functions, as used in multiple attribute utility theory, rather than true fuzzy functions. The creation of suitable membership functions for each attribute is a very important issue and has been thoroughly investigated. This is discussed in Appendix C which includes a brief summary of the main issues related to fuzzy set theory.

Aspiration levels (limits) must be set for each attribute, so that the desirable satisfying solutions can be defined. These must be developed in conjunction with the fuzzy sets and the corresponding membership functions. This is one of the major areas of interest.

Indicative example applications, which were developed and tested in order to provide some initial insight, indicated that simple functions can be used as membership functions for these fuzzy sets. These may include parabolic or sinusoidal and even linear functions among others. These can be used to describe all attributes such as initial and fuel costs, passenger areas, seakeeping performance attributes etc.; there is no particular reason to suggest that more complicated attributes, such as those dealing with subjective passenger preferences, could not be modelled with such simple functions as well.

The development of these initial example applications involved among others the creation of a spreadsheet for the calculation of membership grades according to defined membership functions, the application of defined weightings and the calculation of overall ranking indices based on alternative ranking methods. For the purpose of such investigations the alternative vessels used in the case studies in

[149-151] were used, together with additional variants of these vessels. These were all created by the technical design framework described in Chapters 5 and 6.

This has then been included in the final spreadsheet which performs the decision making calculations and is outlined in Appendix F. Operational requirements are defined, some of them arbitrarily but largely based on existing data as well as common sense and previous experience. These are then quantified and suitable membership functions are defined. The spreadsheet mentioned earlier is then used to perform the necessary calculations. These, as well as other implications arising from such indicative example applications, are discussed in detail in the following chapter which includes a comprehensive example application of the overall model and illustrates various issues relating to all the steps of the technical design and decision making frameworks.

One important observation arising from this application was that the final outcome (ranking and selection) was not the same when different ranking methods were used. Another significant observation was that, in a number of cases, the differences between alternative designs were marginal, making the selection unclear. These two observations ably demonstrate once more the necessity and importance of reliable sensitivity analyses which may well decide the final choice. The insight gained through this investigation was very useful in guiding the research in the development of the decision making framework.

The use of utility functions also addresses the problem of assigning weightings or priorities to the attributes. The definition of weightings, or priorities, for the various attributes is one of the major areas of interest. This should not be done in the same way as in some multiple criteria approaches, where the attributes are directly condensed into one through the use of arbitrarily defined weightings. An approach which involves setting up a matrix of importances derived from voyage simulations has been considered and a number of questions were raised. These mainly involve the determination of the extent to which the performed simulations would be detailed. Simple tests, run in order to provide some insight, indicated that as many as over fifteen parameters may be candidates for systematic variation, showing how cumbersome this process could be. These include economic and operational parameters of varying importance. Parametric variations of some of the major parameters in a typical ferry operation, such as speed and crossing distance, were performed in order to provide some initial insight into the implications of setting up a matrix approach. Some indicative results are shown in Figs. 7.3.1 to 7.3.3, which show the changes in the relative levels of port, maintenance, fuel and capital costs with changes in speed and crossing distance.

These results illustrated the way in which trends and dependencies between parameters and attributes can be seen, for example, showing the increases in relative fuel costs with speed and crossing distance and decrease in relative capital costs. On the other hand this investigation was simplified and indicated the complexity of attempting to develop a more complete approach.

Alternative approaches have been examined, e.g. the possibility of using a 'Bales-type' approach in which the attributes are implicitly weighted by taking into account the range in which they vary between competing designs. It was found that such an approach is well suited to this application where the attributes are normalised in a 0-1 scale in the form of membership grades. In this way if an attribute is considered more important this can be quantified by making the relevant goal (aspirations) more strict, i.e. by narrowing the range of values that are considered satisfactory or changing the shape of the relevant membership function. This leads to more vessels being penalised which is in essence the aim of introducing weightings in a comparative study. Weightings can be carried out by manipulations of the membership functions which have the advantage of being transparent and directly identifiable. This is also discussed in Appendix C.

Other, more sophisticated, approaches to weightings have also been examined, such as Saaty's hierarchical scaling method and other relevant methods. Apart of being notoriously inconsistent in their results, such methods have the additional disadvantage of being too complicated for the needs of a comparative concept evaluation study. In that sense they are also highly unrealistic for the philosophy of the developed model and its potential for practical use. Their further investigation was therefore abandoned.

When all the necessary membership grades are calculated or defined, several methods can be used for ranking competing designs. For purposes of initial investigations a number of them were applied. It seems that the simplest ones are the ones most likely to prove practical and realistic. Currently a simple average is used, as will be discussed in detail in the following chapter. The approach using the minimum (fuzzy intersection) as the criterion for the ranking/selection is also considered, as it is frequently suggested in relevant literature as more appropriate from a strict mathematics (fuzzy set theory) point of view [77-79]. However the use of the average is seen as more realistic from a practical point of view and can be justified if fuzzy sets are in essence seen as utility functions. These are seen in the example application which is discussed in the following chapter.

7.4. Sensitivity Analysis

The importance of performing a comprehensive sensitivity analysis has already been pointed out. The conditions under which a fast ferry operates are far from constant. Operation on different routes during the economic life of vessel is quite common and there are other external factors, e.g. economic factors, which often also vary during the same period. Thus, in order to be commercially and operationally successful, a design needs to have the flexibility to operate with satisfactory economic results under as wide as possible a range of probable scenarios. Since these cannot be accurately predicted, the sensitivity analysis performed at the concept design stage should offer the facility to investigate the available range of probable and even possible scenarios as efficiently as possible.

As has been briefly mentioned earlier, Taguchi's method offers this facility. The method, which is briefly summarised in Appendix D, accounts for the desired flexibility in a design's performance by applying the concept of robustness. This is a measure of the ability of a design to perform well in a number of investigated scenarios while at the same time minimising the variations in its good performance from one scenario to another. The key concept in this investigation is the signal-to-noise ratio which has been defined in the relevant section in Chapter 4. It should be noted that, although the term is used, this is not a S/N ratio in the strict sense as used in numerous technical applications. It is not a simple ratio between a statistical mean and the relevant standard deviation as calculated from the results of the sensitivity analysis, but a more complicated function of these two parameters. In this way erroneous decisions, such as choosing a design with only fair mean performance but very small standard deviation, are avoided. The criterion takes into account both these values separately and leads to the selection of a design which has very high average performance and at the same time small variations between different scenarios, although this design may not have the smallest ratio of mean to standard deviation. It is believed that this leads to a correct choice, or the same choice that would probably be made by a shipowner or operator in a real situation.

The efficiency of the method is attributable to the use of orthogonal arrays (OAs). Alternative scenarios are generated by parametric variations of noise factors (external uncontrollable parameters, see Chapter 4) which are tabulated in OAs. These arrays are specially constructed to allow a reasonably comprehensive investigation of the existing range of combinations between parameter values with a small number of calculations. This is achievable through the pairwise orthogonality of the columns of the array which allows a comprehensive investigation to be performed although only a few combinations are directly investigated. Since the columns, representing a noise factor each, are mutually orthogonal, the effect of each individual factor to the final result can be isolated and investigated separately. It should be noted that, apart from the systematic generation of scenarios and investigation of the available scenario space, this also has potential in the generation of designs and the comprehensive investigation of the design space while reducing the size of the problem significantly. It should be kept in mind that for the method to be applicable certain continuity assumptions must be fulfilled for the selected sets of factors. These are not always easy to verify and this aspect was not fully investigated in the development of the present model.

By focusing on design robustness, what one achieves is in essence the selection of the design that demonstrates the best capability to generate profits for its owner/operator in the widest range of scenarios. It can therefore be seen as a safe choice, as it is one which would eliminate the possibility of extremes and should therefore not create unpredictable surprises during its economic life. Some operators or shipowners might of course be willing to make a riskier choice, i.e. choose a design which has the potential for better performance in some probable scenarios but also the risk of poor performance in other possible scenarios. It is therefore desirable to keep the results transparent, not only in the calculation of the performance of each design in each scenario through the seven primary attributes, but also in the final calculation of the overall measure of merit (S/N ratio) after the sensitivity analysis. This allows the user to see clearly how the decision is made and, if desirable, even make a final choice different than that suggested by the automated algorithm. As will be seen in the following chapter, this facility is included in the developed methodology.

8. APPLICATION OF THE DEVELOPED DECISION MAKING METHODOLOGY

8.1. Systematic Generation of Designs

In the previous chapters all the aspects of the developed methodology have been discussed in detail. This chapter concludes the main part of the main text of the thesis with a discussion on the practical application of the methodology demonstrating all the issues which have been discussed concerning the various steps of the methodology. The starting point is the generation of alternative technical designs through systematic variations of design parameters; this is described in this section.

Orthogonal arrays allow a comprehensive investigation of a wide design range with the minimum number of calculations. This reduces the size of the problem significantly without compromising the validity of the obtained results. The selection of the most appropriate OA for a particular application depends on the number of design parameters (control factors) which are used to define alternative designs as well as on the number of different values each control factor (CF) will have (degrees of freedom). This indicates the number of combinations that need to be investigated to allow a satisfactory coverage of the design space and therefore the size of the OA to be used. These are discussed in more detail in Appendix D which includes a brief summary of Taguchi's method.

An important issue relating to the generation of designs therefore concerns the selection of an appropriate set of control factors. These must be parameters or characteristics which when combined can provide adequate information to define alternative designs and their performance in view of the decision making problem. Their selection therefore depends on the way the performance of competing designs is defined as well as on the technical algorithm applied for the generation of these designs; these have been described in the previous chapters.

In view of these, it became apparent that around ten or more CFs could be necessary to generate designs with adequately defined performance characteristics. The selected set of CFs is given in Table 8.1.1. These include a number of passenger area ratios and hull ratios which allow the calculation of a full set of main dimensions as well as powering and seakeeping performance characteristics.

A few of the hull ratios vary between monohulls and catamarans. The remaining CFs concern the main operating requirements as well as important choices regarding the basic design configuration.

CFs 1 and 2 (see Table 8.1.1) represent the two main area ratios which have been defined in Chapter 5 and allow the calculation of ship areas and a length-beam product as described in the same chapter, combined with passenger and vehicle capacities. These capacities (CFs 7 and 8) have also been included in the set of CFs. This offers the facility to investigate broader and less strictly defined problems where the size (in terms of carrying capacities) and number of the vessels are not considered to be known. In such a case economic parameters would need to be defined in a normalised form (costs per passenger and/or vehicle). For such cases service speed is also included in the set of selected CFs (CF 6).

CFs 3 to 5 represent the major configuration choices, namely main engines, structural material and propulsors. Their inclusion is considered important for a concept design model as they allow different configurations to be investigated in a comprehensive and integrated way. In the second cycle of design generation (see Section 4.3 and Fig.4.3.1) these will not be included in the reduced set of CFs as the distinct choices they represent will have been made as indicated by the results of the first cycle. The same is true for CF 13, diesel engine speed, which is a secondary parameter included for broader investigations to allow the examination of an additional configuration choice between high- and medium-speed diesels when such engines are used.

CFs 9 to 12 include the main hull ratios which, combined with the area ratios (CFs 1 and 2), allow the calculation of a full set of main dimensions (see Section 5.3 and Figs. 5.3.1 and 5.3.2). These are therefore very significant parameters which will be included in every case, even in problems where the number of CFs is reduced from its maximum value of 13. The selection of these specific hull parameters was influenced by the fact that they are used as major parameters in the systematic series for powering and seakeeping calculations, see Chapter 5 and Appendix G.

This comprehensive set of control factors offers the facility to generate designs of significantly different characteristics and therefore to investigate a wide design space. Orthogonal arrays are then used to allow this to be performed efficiently by tabulating a reduced number of factor value combinations which do cover as wide as possible a design range. This has been mentioned earlier in this thesis and is also discussed in Appendix E which also includes some of the OAs which are of interest for the needs of this model.

There is a wide range of standardised OAs created through years of research on the field and these can be found in related literature [54-55]. It was decided that the L27 array could be suitable for the purposes of this model, as it allows the tabulation of 13 factors at 3 levels each. If less than 13 factors need to be investigated then the remaining columns are simply left empty without any effect on the obtained results. This OA generates 27 designs which adequately cover the whole design space so that a near-optimum solution can be reached very quickly through the developed algorithm. The benefits in terms of problem size reduction can be easily seen; a full factorial investigation would require the generation of $3^{13} = 1{,}594{,}323$ designs. If less CFs are considered adequate then smaller OAs can be used, a good example being the L18, which can include up to 8 factors, 7 at 3 levels and one at 2 levels, generating 18 designs. This particular array is called an engineering array as it is designed to have characteristics that make it particularly suited for investigating situations that are usually encountered in engineering problems, and therefore its use would be appropriate for this investigation [51-55].

It is in general desirable to allow control factors, at least most of them, to take at least three values. This allows trends to be seen by providing a rough idea of the curvature of graphs representing factor effects to the overall design performance. This is of course applicable only to factors which represent continuous parameters and not to those representing distinct configuration choices for example. These will be seen in the discussion of the application of the method.

By this systematic variation of CF values 27 (or 18) designs are generated: main dimensions are calculated through the area-based approach described earlier; resistance and propulsion calculations are performed using systematic series data and relevant regression formulae; and masses are estimated using a combination of available data and techniques. These can be seen in Section 8.4 which outlines the practical application of the whole methodology, accompanied by a comprehensive example application and discussion of the results.

8.2. Systematic Generation of Scenarios

For the calculation of the performance characteristics as described in Chapter 6 several external factors need to be known. These include economic factors, necessary for the calculation of costing attributes, and environmental factors, necessary for the calculation of seakeeping attributes. However, although these factors may be known for an initial set of conditions at the time of the vessel's design, some of them may change during the vessel's operating life. These are the noise factors which make the development of a sensitivity analysis algorithm necessary.

Alternative scenarios are generated systematically in the same way as alternative designs. In this case noise factors are varied in the same way as control factors and different combinations of values are tabulated in orthogonal arrays. This allows the investigation of the sensitivity analysis discussed in Section 7.4. As with the systematic generation of designs, the selection of appropriate OAs depends on the number and degrees of freedom of the noise factors. The definition of a set of noise factors must therefore preceed the selection of OAs and the consequent scenario generation.

Table 8.2.1 shows the selected set of noise factors. Four main NFs (NFs 1 to 4) were selected as a minimum for the high-speed ferry investigation, namely fuel price, significant wave height, wave period and required power margin. The former is an evident and typical choice, affecting directly and greatly the economic calculations, while the last three are used to take into account the possibility of switching the operation of the vessel to different routes, which is quite common for fast ferries. These four NFs offer the facility to investigate the effect of the main and most common economic and environmental variations.

Additional NFs include operating profile parameters such as trip length, speed restrictions and operating period. It is evident that rerouting of a vessel may involve routes of significantly different characteristics not only in the environmental sense (sea states). Alternative routes may be shorter or longer and have different operating restrictions and such operational implications may have direct effects on the economic calculations. It is therefore desirable to have the facility to investigate these and noise factors such as crossing distance, speed restriction distance, reduced speed and so on can offer this facility. Also, economic factors such as borrowing and loan repayment parameters, opportunity interest rate and economic life (or alternatively a capital recovery factor) may be included if desirable.

Unlike control factors, it is generally considered that for noise factors it may be adequate to assign only two different values to each factor. However this allows only for a basic sensitivity analysis to be performed. Although this would allow a further reduction to the problem size by allowing the use of smaller OAs, it was decided to use arrays which can accommodate over two levels for the noise factors as for the control factors. A more comprehensive sensitivity analysis could be investigated in this way.

Among numerous existing OAs, the L9 was selected as the best suited for this investigation in its minimum form, as it can include 4 factors at 3 levels each, see Appendix E. Nine scenarios will therefore be defined and the performance of each competing design will be calculated for each one of these scenarios. If more NFs need to be examined then larger OAs can be used, a good example being the L18 as discussed in the previous section. Again the beneficial effect of using OAs can be seen; if a full factorial was used then the L9 would need to be replaced by $3^4 = 81$ combinations and the L18 by $3^7 x2 = 4374$ combinations. Even larger arrays such as the L27 can be used if desirable in order to allow more complicated sensitivity analyses. However it is considered preferable to keep the size of the analysis to reasonable levels which allows increased transparency as the results and separate effects of various factors can be clearly seen, without on the other hand making the analysis too oversimplified and incomplete. The L18 is considered a good solution in view of these considerations.

As the systematically generated scenarios are defined the performance characteristics of each design can be calculated for each scenario. Seakeeping calculations are performed using the specified environmental parameters and costing calculations are performed taking into account the fuel price and any operating parameters. These can also be seen in Section 8.4. The last step, after designs and scenarios have been systematically generated and performance calculations have been executed, involves the definition of an appropriate ranking criterion for comparing the competing designs which then allows the final choice to be made.

8.3. Overall Ranking Based on Design Robustness

The previous sections have described how alternative designs and scenarios are generated and the performance characteristics of each design calculated for each scenario. The next step is the calculation of the primary attributes and their uniform quantification using fuzzy sets in each case, as described in Chapter 7. This allows the definition of an overall ranking criterion combining all the attributes and therefore indicating the level to which each vessel satisfies all the primary goals.

8.3.1. Ranking Index

The quantification of the seven primary attributes using fuzzy sets is carried out in the standard way. This can be seen in detail in the worked example application in the following section. Limits are set for each attribute (aspirations) which correspond to the relevant goals and therefore define the targets each design needs to reach in order to be considered of fully satisfactory ($m = 1$) or simply adequate ($m > 0$) performance with respect to the particular goal. Appropriate membership functions are then defined to determine the membership grades of designs with performance between the two limiting values. The shape of each function should represent the user's perception of the importance of the relevant attribute and variations in the performance of different vessels with respect to the attribute.

When the membership functions are defined seven membership grades are calculated for each design in each scenario. In this way for a given scenario the performance of each design is described by seven numbers in the range 0 to 1. These provide a directly recognisable representation of the performance characteristics of each design but they still need to be combined into a single criterion. Different ways of achieving this exist and they have been investigated; it was found that using a simple average of the seven membership grades is a satisfactory approach and it is considered that applying more complicated methods does not offer any particular advantages to justify the additional calculations. Of course this implies a simple (equal) weighting between the factors considered but there is no evidence to suggest that more complex methods could be justified at this stage. The final overall ranking index is therefore again a number between 0 and 1 for each design in each scenario. Another simple criterion that could be considered is using the minimum of the seven membership grades. As was mentioned in the previous chapter, this is considered more correct from a strict mathematical point of view [77-79], however it is considered less realistic in the context of the practical application in high-speed ferry selection.

It can be seen that by applying the simple average as a final criterion no weightings are taken into account. This may at first be questioned but in fact it is highly desirable according to the discussion given earlier, see Section 7.3. By applying the developed approach the different attributes are implicitly weighted by changes in the shapes and limits (aspirations) of the respective membership functions which can represent the perceived importances of the attributes. As was discussed earlier this eliminates the need to apply user-defined weightings which are not so easy to apply in such a transparent manner. By manipulating the membership functions and goals instead, the user has the ability to make decisions which affect directly recognisable features to which one can relate more easily.

An alternative approach might entail the application of a cost-benefit analysis. This has not been applied in the current study. In the context of the developed model this would entail separating the two costing attributes from the rest and possibly condensing them into one. This would allow the investigation of a cost-benefit analysis in which the five remaining attributes would be combined in the same way described in this section to represent the benefit as defined in such analyses. Such an approach can be justified by noting that costing attributes are qualitatively different than the rest, representing what a shipowner or operator has to pay in order to get, in terms of performance, what is described by the other attributes. A cost-benefit analysis would then indicate designs that would be non-dominated in the usual sense and allow the user to make a final selection between them in a way that might be similar to the one presented here. In such an analysis the five 'benefit' attributes might even be condensed into two, by integrating the three seakeeping-related attributes into one global seakeeping performance attribute and the remaining two (accommodation quality and attractiveness) into another which would represent overall passenger attractiveness. Such an approach may be attractive to practitioners and it would therefore be worthwhile to investigate its potential and implications in the future.

8.3.2 Signal-to-Noise Ratio

Through the use of the ranking index the performance of each design can be calculated and competing designs can be compared and ranked in each scenario. However the ultimate goal is to make a final selection based on broader considerations, i.e. taking into account different scenarios. This is the selection based on design robustness which is achievable through a sensitivity analysis and is indicated by calculating an appropriate signal-to-noise ratio.

As the quality function in this application is to be maximised, the S/N ratio must be of the 'larger is better' type. This is defined as:

$$\eta = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{8.3.1}$$

where η is the S/N ratio for a certain design (combination of control factor levels), y_i is the value of the quality function in the i-th scenario for that design and n is the number of scenarios (different combinations of noise factor levels) examined for each design. As can be seen by its definition, and considering that the y_i values will all be between 0 and 1 (values of the overall ranking index defined earlier), this S/N ratio will take negative values. A higher S/N always demonstrates a more robust design, thus in this case the better design will be the one with the lowest absolute S/N value (closest to 0); zero would correspond to a fully satisfying design, i.e. one that fulfils all the requirements in all the scenarios, something highly unlikely in practice.

The S/N ratio is a criterion which combines both the average performance and the relevant deviation, allowing a selection which would not have been straightforward otherwise, see discussion in Section 7.4. When comparisons of mean values and standard deviations give conflicting results the S/N ratio helps resolve the issue and indicate the final outcome. It is apparent that in cases this may still be marginal between some of the competing designs. It is for this reason that it is desirable to present the results in a transparent way that allows the user to see clearly how the performance of each design varies from one scenario to another. The model should not operate as a 'black box' which imposes a solution to the user; it should rather present the user with a set of satisfactory solutions and suggest one among them while allowing them to choose another solution if desirable. These can be seen in practice in the worked example in the following section.

8.4. Application of the Method

8.4.1. Outline

A summary of the way the developed methodology, as outlined in Section 4.3 and Fig.4.3.1, is applied is given here. This describes the followed sequence of steps including those discussed in this chapter and the techno-economic calculations described in Chapters 5 and 6. A worked example application is given in which the actions outlined here can be seen in practice. It should be noted that the summary given here is more detailed than the initial outline of Section 4.3; the number of steps described here is therefore higher and does not correspond to the seven broad steps shown in that section.

1. First the size of the problem is defined by deciding which variables will be considered constant and which will be treated as parameters. This depends on the actual situation which is being investigated. Specifically it must be decided which design and which operating parameters will be varied, which will affect the size of the design generation and the sensitivity analysis arrays respectively.

2. Alternative designs are generated by systematic variations of the selected design parameters (control factors), tabulated in an appropriate orthogonal array, probably the L27 or L18. The values these parameters take (control factor levels) are indicated by the ranges in which these vary for the existing vessels included in the database and any additional considerations or requirements that may reduce or extend, if allowable, these ranges. Each design is then defined by its principal characteristics as described in Chapter 5 by performing the relevant technical calculations.

3. Varying scenarios are generated by systematic variations of the selected noise factors using an appropriate orthogonal array, most probably the L18 or L9. Operating, environmental and economic considerations relevant to the situation under investigation indicate the noise factor levels. Seakeeping and costing calculations as described in Chapter 6 are performed for each design in each scenario thus defining the performance characteristics in each case.

4. The seven primary goals are set which represent the main requirements the designs need to meet in order to be considered satisfactory. This is initially

done in simple language terms as they would be defined by a shipowner, operator or other user of the model.

5. The primary goals are quantified using fuzzy sets. Aspiration levels and appropriate membership functions are defined which describe the requirements coded in the wording of the primary goals.

6. By using these membership functions the seven primary attributes calculated in step 3 are quantified in the form of membership grades for each design in each scenario. Their average in each case represents the relevant overall ranking index (quality function).

7. A signal-to-noise ratio is calculated for each design using Eq. (8.3.1). This indicates the better design among those tested. This may not be the overall better design among all the possible combinations of CF levels.

8. The independent effects of each CF to the S/N ratio are investigated, as is possible because of the orthogonality of the arrays. This indicates the optimum combination of CF values and thus the overall better design. This concludes the first cycle leading to the selection of the design to be used as a starting point for the second cycle. If different hull types are being investigated, as is the goal of the model, then this procedure has been performed in parallel for say monohulls and catamarans and the result is one monohull and one catamaran to be used as starting points for the second cycle in each case.

9. A second cycle (steps 2 to 8) is performed in exactly the same way as the first cycle. This time the OA used for the generation of designs is smaller, probably the L18 or L9 as has been discussed earlier. The reduced set of CFs are varied within narrower ranges closer to the values that defined the final better designs of the first cycle in step 8. By completing step 8 of the second cycle a near-optimum monohull and a near-optimum catamaran have been found.

10. The final choice, as suggested by the method, is now straightforward by simply selecting the design with the highest S/N ratio. However the detailed results for all the designs can be seen and the user may make a different choice if desirable for any reason.

8.4.2. Example Application and Discussion

A comprehensive application of the developed methodology is given here. This demonstrates the practical application of the methodology as outlined earlier. In this application the tools that have been developed as part of the research programme have been used to the maximum extent possible, i.e. allowable by their level of development; the level of completion of the modules allowed most calculations to be performed normally within the developed framework.

Step 1. For this application the case study involves a vessel to carry 620 passengers and 160 cars at 36 knots over a 40 n.m. route. The details of the assumed operating profile are given in Table 8.4.1. It can be seen that in this example capacities and speed are considered constant rather than treated as design parameters, which assumes that market research has been undertaken leading to the definition of specific requirements for the vessel. This allows the use of the L18 array for the systematic generation of alternative monohull and catamaran designs. The operating profile characteristics are not varied either in this illustrative example, allowing the use of the L9 array for the systematic generation of scenarios. However, if desirable, these can be varied without any implications by simply using a larger OA such as the L18.

Step 2. Through the use of the L18 array, 18 monohull and 18 catamaran designs are generated. The two vessel types are in essence investigated in parallel with separate arrays, as is shown in Table 8.4.2. For each design (combination of control factor levels) the principal characteristics are calculated using the technical design framework. This includes estimation of main dimensions, powering calculations and mass estimates.

Step 3. The NF values which are used for generating the 9 different scenarios are shown in Table 8.4.3. For each design and each scenario the scenario-dependent performance characteristics are calculated. These include costing estimates and seakeeping performance calculations.

Step 4. The set of assumed operator's requirements (primary goals) are given in Table 8.4.4. For example, the goal for the building cost attribute is that 'it should be preferably less than $33 million and definitely less than $40 million'. This wording indicates that a vessel costing $33 million or less is considered fully satisfactory as far as the building cost attribute is concerned and a vessel costing just under $40 million is considered marginally acceptable, as can be seen in Table 8.4.4. Similar considerations apply to the other primary attributes noting that, depending on the wording of the relevant goals, in some cases only one of the two limits is specifically defined. These indicate the limits for the definition of appropriate membership functions.

Step 5. The primary goals are fuzzified using appropriate sinusoidal, parabolic and linear membership functions, see Table 8.4.5 and Fig.8.4.1. These simple function types have been found to be adequate for modelling most goals in the context of fast ferry concept design and decision making. It is considered that sinusoidal functions may be better suited to modelling goals which are not defined very specifically, such as fuel cost and attractiveness in this example. On the other hand the selection between parabolic and linear functions is arbitrary, depending on the personal perception of the user and for this illustrative example application they were assigned to the various goals as seen in the relevant table and figures.

Step 6. Membership grades are calculated for all primary attributes in each case using the membership functions defined in the previous step. The performance of each design is therefore defined in each scenario by seven numbers between 0 and 1 (membership grades). These are compounded into an overall ranking criterion by taking their average in each case (ranking index), according to the detailed discussion given in the previous sections.

Step 7. A S/N ratio is calculated for each design from its nine ranking indices, one for each scenario, using Eq.(8.3.1).

Step 8. The first cycle is completed by selecting the two designs, one monohull and one catamaran, to be used as a starting point for the second cycle. These are the designs with the highest S/N ratios among all 18+18 designs tested for the two hull types.

Step 9. The second cycle is performed, using the small L9 array for the generation of designs closer to the ones selected in the first cycle, as seen in Table 8.4.6. It can be seen that in the second cycle only the basic hull parameters are varied. The passenger area parameter has been compounded into a direct calculation replacing the two-step calculation ($N_P \rightarrow A_S \rightarrow A_P$) used in the first cycle; the latter allowed increased flexibility for the initial design generation and is not necessary anymore. Also the basic configuration parameters are not included as the relevant decisions have now been made: as expected for such a vessel, the main engines are diesels, hull material is aluminium alloy and the propulsors are waterjets. The same sequence of calculations is performed for the same scenarios and a S/N ratio is calculated for each of the new designs. The results are seen in Table 8.4.7 for catamarans. The effect of each individual CF on the S/N ratio can now be examined directly due to the orthogonality of the arrays. This indicates the optimum level (value) for each CF and thus the optimum combination of CF values. This in turn defines a new design in each case (monohull and catamaran) which is very close to the true optimum for each vessel type. This may not be one of those that have been already tested in which case it can be verified that it has a S/N ratio higher than all other designs.

Step 10. All the necessary calculations are performed for the best monohull and the best catamaran which can then be directly compared through their S/N ratios, thus reaching the final choice.

Table 8.4.7 shows that the better among the 2nd-cycle catamaran designs is No.7, as it has the highest S/N ratio. However this may not be the overall best. The effect of each individual CF on the S/N ratio can be examined by simply taking the average S/N of the three designs that have a specific CF value. This indicates the best value among the three used for each CF which in turn defines the optimum combination and thus the best design. For example, if one examines the A_P/N_P parameter (CF1), it can be seen that the first three designs have the lowest value (1.70), the following three have the middle value (1.80) and the last three have the highest value (1.90). If one compares the average S/N ratios for each of these three groups, see Table 8.4.7, it can be seen that the middle group has the highest average. This indicates that 1.80 is the best value for this parameter. In a similar manner the optimum values for the other three CFs are obtained; these are: $A_P/N_P = 1.80$, $S/L = 0.24$, $L/\nabla^{1/3} = 9.4$, $B_H/T = 1.9$. The design with these characteristics will be the best one among all the possible (81) parameter combinations; this is not one of the nine combinations that were tested. When all the necessary calculations are performed for this new design it is seen that it is indeed better than design No.7: its final measures of merit are $\mu = 0.923$, $\sigma = 0.011$ and ultimately $\eta = -0.698$.

Similarly for monohulls it is found that the optimum combination is: $A_P/N_P = 1.80$, $C_B = 0.40$, $L/\nabla^{1/3} = 7.7$ and $B/T = 5.5$. Again this was not one of the nine combinations that were tested; a new design which will be the overall best is therefore generated and, by performing all the necessary calculations, it can be verified that it is indeed better than the initially better design, which was No.9. For this monohull the final measures of merit are $\mu = 0.892$, $\sigma = 0.021$ and ultimately $\eta = -1.035$. It can be seen that it is better than most catamarans, but not as good as the best one. The overall best design, i.e. the most robust and consequently the most suitable for the particular service under investigation, is therefore a catamaran with the characteristics shown in Table 8.4.8. This can be considered a good starting point for the detailed design process.

It is interesting to note that careful examination of the tables directly reveals information which proves the necessity of performing such a comprehensive sensitivity analysis and indicates the merits of the adopted approach. For example, it can be seen in Table 8.4.7 that if only the initial scenario No.1 was investigated then design No.8 would seem to be one of the best choices, ranking third with a high ranking index of 0.901; however the sensitivity analysis reveals the quick deterioration of its performance at rougher weather conditions (scenarios 4-9) and it ends up being the worst design with a final S/N of –4.317. Similarly, if only scenario No.1 was investigated then design No.5 would appear to be better than design No.6 (ranking index of 0.920 versus 0.899); however the latter is more robust as the sensitivity analysis reveals, its performance remains practically the same at all scenarios and in the end it actually ranks second among the nine tested designs with a S/N ratio of –1.073.

The fact that such observations can be made so easily and directly demonstrates a major strong point of the methodology, which is due to the application of the Taguchi-type approach and the orthogonality of the arrays. Apart from such comparisons, it is also possible to directly assess the effect of each noise factor to the performance of each vessel. For example, the last three scenarios (No.7-9) correspond to the highest significant wave height value and it can be seen how some designs suffer heavily in these cases (e.g. design No.8) whereas other designs, such as No.7 and No.6, seem not to be significantly affected. Similarly, scenarios No.3,5,7 correspond to the highest fuel price and it can be directly seen which designs are more vulnerable to price increases, while again designs No.7 and No.6 demonstrate a very robust performance.

In order to assess the effect of variations in operating parameters a few additional example variations have been tested. It is reminded that in the basic example the operating parameters have been kept constant. First the crossing distance was increased to 80 n.m. This led to practically the same results, which for this reason are not presented here. This is due to the fact that the range of the vessels is considered to correspond to daily autonomy, thus an increase in crossing distance only leads to a reduction in the number of crossings per day, but the daily fuel consumption remains the same and therefore so does the running cost (other effects of reduced crossings are insignificant); crossing distance would not affect any other attributes in any case.

This could be seen as an indication that the decision not to vary operating parameters is correct. On the other hand variations in parameters such as speed restrictions for example might have more significant effects on the overall results. In the same context, variations in service speed would affect the results more strongly, as they would affect both building and running costs (increases in installed power would lead to higher machinery and fuel costs) and at the same time they might affect seakeeping performance attributes as well. It was therefore decided to investigate the effects of speed variations, at least at a relatively simple level. It should be kept in mind that, as has been discussed earlier, at present the model does not include a mass balance facility and the displacement is calculated through geometric considerations only. This does not allow, for example, the effects of deadweight changes to be taken into account when varying operating parameters, which could possibly lead to the generation of altogether different designs (including new dimensions). At the moment the geometrically calculated displacement is considered to be correct.

If the speed requirements are changed the effects on each of the primary attributes can be examined, indicating how different results may be obtained. For this investigation an increase and a reduction of speed by 2 knots to 38 and 34 knots respectively are considered. All other considerations and requirements are considered to be unchanged. It would be possible to alter the assumed operator's requirements in parallel to the speed change, e.g. accept higher costs for the higher speed. It was however decided to assume that the requirements remain the same and examine the effects to calculated vessel performance of say a higher speed requirement with constant costing and seakeeping limitations. The effects of such speed changes can be summarised as follows. It should be kept in mind that, as discussed earlier, the 'designs' with the strict sense of the word, i.e. including dimensions only, remain the same as speed does not affect the estimation of main dimensions. It is also reminded that increases or reductions to draught or displacement through different machinery installations, for example, are not taken into account at this stage as has been discussed in detail and the geometrically calculated displacement is still assumed to be correct.

Building costs change as the machinery costs change. Hull and outfit costs remain constant as dimensions and passenger areas are not affected. The effects on main machinery component costs can be seen from the equations in Table 6.2.2. For example, diesel engine cost varies linearly with changes in installed power. Changes in turbine and gearbox costs are more pronounced while for waterjets the effects are less significant. As machinery cost is the most important component of building cost, these changes can affect the building cost attribute. Since the building cost membership function is in this example parabolic, see Fig. 8.4.1, the effects are greater for ships closer to the upper end where the slope of the curve is higher; on the other hand for ships closer to the lower range end (in other words cheaper ships) the changes in the attribute values are smaller. In the initial example building costs were roughly similar for monohulls and catamarans and as monohulls are more sensitive to powering issues the building cost attribute now becomes slightly in favour of the catamarans for the increased speed while the effect is marginally reversed for the reduced speed.

Similar effects, originating from the changes in installed power, are observed for the fuel cost attribute. Specific fuel consumption is directly proportional to installed power, it therefore increases, resp. drops, by approximately 17-18%. At the same time, however, the trip time and consequently the daily operating hours are reduced (increased) by 5.5%. As a result, the overall change in fuel cost is of the order of 10-11%. This is again in favour of the catamarans when the speed is increased, further enhancing their advantage over monohulls; in the case of reduced speed the difference is slightly reduced, still remaining of course in favour of the catamarans.

The passenger area attribute remains the same as has been discussed. As for the attractiveness attribute, according to its basic definition it would not be affected by speed changes either. However, if speed is seen as a variable rather than constant then it should be included in the calculation of the attractiveness index. As this is not fully developed yet and only roughly estimated values have been used for the initial example, proportional variation of the existing indices with speed is assumed. It can be seen that this leads to stronger effects to vessels with higher initial attractiveness indices.

The remaining three attributes are the seakeeping-related ones, namely motion sickness incidence, power increase in waves and availability. These are important attributes, however it can be seen that for the speed range under consideration a change of 2 knots does not have significant effects on seakeeping calculations. Motion sickness incidence is the least affected as the small negative effect of a speed increase is balanced by the reduction in crossing time (reversed considerations apply similarly to the case of speed reduction). Power increase, defined in terms of a percentage, is not significantly affected either, and the same is true for the availability attribute. Any changes are in favour of the monohulls in the case of increased speed, expanding their lead over catamarans in these attributes. As M.S.I. and power increase are modelled by parabolic functions, the same comments apply as for the building cost attribute concerning which designs will be most affected. The availability attribute, on the other hand, is modelled by a linear function and therefore the effects are evenly spread throughout the attribute value range.

Although not all these details can be quantitatively investigated in full, it is apparent that for the 38 knot case the winner will again be a catamaran, this time with an increased margin over the monohull, while for the 34 knot case the results are becoming marginal and in fact the monohull may well win. This is to a great extent consistent with the situation in the fast ferry market where it can be seen that, at the vessel sizes under consideration, monohulls are increasingly successful for speeds up to about 35 knots while for speeds approaching 40 knots catamarans dominate. For both vessel types the comparative effects of the speed changes are smaller between vessels of the same type than between monohulls and catamarans. Hence the 'best' of each hull type will again be found among the few top-placed designs of the initial example. Furthermore it can be observed that measures of merit, ranking indices and signal-to-noise ratios, are lower for the increased speed and higher for the reduced speed. This is because, as the operator's requirements have been kept constant, in the case of a speed increase for example the negative effects on costing and seakeeping attributes cannot be outbalanced by any positive effects on say attractiveness. This outcome might of course have been quite different if the main requirements had been changed in view of the new speed requirements or if the investigation was focusing on a different speed range where, for example, speed reductions might cause seakeeping performance to deteriorate rather than improve.

This application showed that the modular technical design framework offers the facility for comprehensive techno-economic calculations and, combined with the Taguchi-type overall model structure, facilitates the rapid generation of feasible and realistic alternative designs. The specially developed algorithm for the calculation of main dimensions contributes to this, used in conjunction with the suite of robust databases created as part of the research programme. These databases facilitate the development of reliable technical and costing modules and allow significant flexibility as they, and consequently the relevant modules, can be constantly updated to include new data.

The efficiency of Taguchi's method was also made apparent, as the overall best amongst all possible combinations (designs) can be found by generating and investigating only a small number of designs. This allows the quick definition of a near-optimum design which can be considered a good starting point for the detailed design process.

As an additional step an optimisation may be carried out if desirable, using this design as the starting point whose near-optimality would ensure quick convergence to an overall optimum with any optimisation technique. It is however considered preferable, according to the philosophy of the developed methodology, to retain the results in the form shown in the example application, which allows the required transparency and flexibility in the final choice. An alternative option which may be worthy of investigation involves including a more sophisticated search algorithm in the first stage of the methodology. This could for example replace the first cycle of design generation, e.g. [48]; in such a case a one-cycle investigation can follow leading directly to the final solution through the use of the larger L18 or L27 design arrays.

The decision making model can be used for a selection between competing designs of any number of different hull types. Provided that the necessary technical information for the calculation of the primary attributes is available, the model can be used for all possible hull types simultaneously without any implications, due to the selection and definition of the primary attributes and the quality function. However, for the application of the whole framework to different hull types, appropriate design tools and data must be available to allow the generation of designs of all hull types.

This application has demonstrated that the proposed methodology can be quickly applied and produce results that are adequately reliable for the needs of concept-stage design. The process is efficient, easy to use and flexible, allowing virtually any high-speed ferry selection problem to be investigated quickly without any modifications. It is therefore believed that the developed methodology offers a useful tool for concept exploration studies as it combines a number of characteristics which would make it attractive to potential users such as high-speed ferry operators and designers.

9. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

9.1. High-Speed Ferry Design and Decision Making

9.1.1. High-speed ferries require a specialised approach to their concept design and the related decision making problem. This is due to a number of special characteristics these craft possess, mainly: (a) the wide variety of hull types and configurations available for high-speed ferry services; (b) the sensitivity of these craft to variations of external factors which occur during a vessel's operating life; and (c) the subjective nature of passenger requirements which affect the commercial potential of high-speed ferries.

9.1.2. There is a lack of available historic or systematic data as well as design tools and techniques for high-speed ferries. Existing published data and tools for conventional vessels cannot be applied for high-speed ferries which possess distinct characteristics such as lightweight construction materials and machinery installations, novel hull forms and configurations, and different economic parameters. As these vessels represent a relatively recent development, their design still seems to be carried out largely in an ad hoc manner by a limited number of established designers and shipyards. There is therefore scope for a systematic design methodology for high-speed ferries; such a methodology must be both robust and flexible in order to cope with this relatively recent but rapidly developing vessel category.

9.1.3. Alternative decision making techniques and approaches exist; however, they have shortcomings and limitations reducing their potential for use in the high-speed ferry market which possesses the special characteristics outlined earlier. It is apparent that there is scope for a specialised approach to this particular decision making problem, i.e. selection between alternative high-speed ferry designs of the most suitable for a particular service. Such an approach must be realistic by taking into account the special characteristics of high-speed ferries and the related decision making situations. At the same time it must be transparent and reasonably simple to use and understand, in order to be of practical importance to potential users such as designers or operators.

9.2. Developed Methodology (General)

9.2.1. The proposed methodology has the necessary characteristics to satisfy the requirements outlined in the previous section. It is robust due to the creation and use of databases, the analysis of which leads to reliable results. At the same time it is flexible as it is based on a modular structure which can be easily updated and has the facility to incorporate theoretical tools to enhance the scope of the databases. Furthermore, the methodology is efficient due to the application of a Taguchi-type approach. Finally, the adopted primary attribute approach allows increased transparency in the obtained results.

9.2.2. The development and structure of the overall model are such that it can cope with alternative vessel types, mainly monohulls and catamarans. This is a significant characteristic of the model, as the facility to investigate different hull types or configurations simultaneously is of great importance for high-speed ferry selection problems. Existing models often do not have this ability. Monohulls and catamarans make up the majority of operating high-speed ferries of current technology. The concept design framework allows comprehensive investigations of these two major vessel categories for which adequate systematic and historic data are available or can be generated. The decision making framework on the other hand allows comparisons between vessels of any possible hull form and configuration to be carried out. This is due to the structure of the decision making methodology, including the careful selection and definition of the set of primary attributes and the relevant goals. These are based on operational and commercial requirements which are common for all competing vessels and therefore eliminate the effects of varying hull types or configurations.

9.2.3. The developed methodology is realistic, practical and well suited for concept-stage investigations of high-speed ferries. The use of a limited set of primary attributes to determine the merits of competing designs seems to be the best way to address such problems at the early stages where detailed techno-economic and other information cannot be accurately known. Furthermore the definition of the performance of competing vessels based on operational and commercial considerations is appropriate for high-speed ferries. Such considerations determine the potential for profitability of each vessel which cannot be based on assumptions about capacity utilisations as in the case of cargo vessels. Unlike cargo vessels, for high-speed ferries the ability to attract income, which in this case comes in the form of passengers, partly depends on their ability to satisfy requirements which are not easy to quantify. These are modelled by operational considerations such as seakeeping performance, operational reliability and quality of accommodation. Defining the performance of competing vessels by means of satisfying these requirements, together with commercial requirements such as life-cycle costs, helps indicate the potential for commercial success of each vessel in a realistic manner.

9.2.4. Tests, case studies and example applications have demonstrated that the developed methodology can be applied quickly and give results which are reliable and adequately accurate for the needs of concept design. It is simple to use and can be easily formulated so that it can be applied in a mechanised way.

9.2.5. The developed model offers the facility for comprehensive investigations covering the range of current-technology vessels. Although developed as an integrated approach it can be seen as consisting of two separate parts which can in principle be used independently, namely the concept design framework and the decision making framework. The concept design framework may be used for the systematic generation of alternative high-speed ferries where all the necessary technical and economic calculations can be performed within the modular shell. On the other hand the decision making framework may be used for the comparison, ranking and selection of designs even if they have not been created by the concept design framework. For example it may be used for comparing existing or commercially available designs or designs generated by other concept exploration models. However the combined use of the two frameworks gives the best results as it takes advantage of the increased compatibility they offer, having been developed in parallel in the context of the overall model.

9.3. Concept Design

9.3.1. Complete calculations of a set of main dimensions can be performed for high-speed ferries based only on carrying capacities, i.e. numbers of passengers and cars. Speed, expressed by means of Froude number, seems not to affect the hull ratios of such craft and therefore the calculation of their main dimensions. Reliable, realistic and feasible main dimensions can be rapidly calculated using an area-based approach where capacities are the input while area and hull ratios are systematically varied as parameters. The algorithm offers flexibility in the parametric variations and a satisfactory level of reliability due to the use of a large and robust database.

9.3.2. Systematic calm-water resistance series offer comprehensive coverage of a wide range of round-bilge hulls, both for monohulls and for catamarans. Propulsion calculations can be performed using systematic data for propellers and statistical data for waterjets. Complete powering calculations are possible using such data. It would be desirable to enhance the scope of the powering module by including other hull types, such as deep-vee and chine hull forms. Data for such hull types are limited at present. Further work should also focus on completing the extension of Series 64 to include catamarans. This will further enhance the scope of the powering module allowing a wider range of hull forms to be investigated.

9.3.3. Accurate and reliable mass estimates are important yet can be difficult to achieve for high-speed ferries. Such vessels are sensitive to inaccuracies in mass estimates. At the same time the use of lightweight hull materials and advanced machinery installations and other equipment creates additional complications for such calculations at the initial concept design stages. It is possible to perform detailed estimates of hull, machinery and outfit masses provided that necessary data are available and specialised algorithms are developed. Initial investigations into such data and algorithms currently under further development have indicated that such an approach is feasible and can give reliable and reasonably accurate results and therefore merits further investigation.

9.3.4. Seakeeping considerations have significant effects on the performance of high-speed ferries. They directly affect passenger comfort and overall satisfaction as well as other important issues such as structural integrity and operational limitations. These are critical in comparative investigations and have a significant influence on the choice between competing vessels. Such aspects therefore need to be taken into account within any high-speed ferry investigation and for this to be possible good data are necessary. The definition of exceedance limits for responses such as motions and accelerations can lead to the quantification of both operational limits and passenger comfort aspects (e.g. motion sickness incidence). Such aspects are addressed within the seakeeping module which allows the relevant calculations to be rapidly performed. There are however some limitations on the scope of the module, which currently includes only data for regular head seas. Its scope would therefore be enhanced by the addition of data for oblique and beam as well as irregular seas; such data are under development and this is in general an area where further research is likely to be particularly useful.

9.3.5. Building and running costs are particularly important for high-speed ferries. These craft are expensive both to build and to run and also sensitive to the effects of external and/or uncontrollable factors. It is therefore important to establish reliable and accurate algorithms for initial costing estimates at the early design stages. Running costs can be directly calculated using the operational parameters of the vessel together with basic technical characteristics such as installed power. For the calculation of building costs on the other hand certain data and algorithms are necessary. Detailed tests have indicated that reliable results can be obtained both for total building costs and for more detailed breakdowns of costs into hull, machinery and outfit costs. For the latter (more detailed) calculations further work is necessary. Initial investigations have shown that developing such an approach is plausible and good results can be obtained without the need for particularly complicated calculations.

9.3.6. Complete techno-economic calculations can be performed within the developed concept design framework by using the suite of programs and databases it includes. This provides a robust framework and reliable results while the modular structure gives increased flexibility.

9.4. Decision Making

9.4.1. The broad philosophy of multiple criteria decision making methods has attractions for concept-stage decision making problems. Such methods allow the investigation of goals which are of significantly different nature and often involve conflicting criteria. Used in combination with Taguchi's method a multiple criteria approach proves well suited for the high-speed ferry selection problem. It must however be carefully formulated and applied, taking into account the special considerations relating to the particular problem.

9.4.2. The approach using a limited set of primary attributes for the definition of the performance of alternative designs has significant advantages and is particularly suited for concept-stage investigations. It allows the definition of a concise yet comprehensive summary of the merits of each design in view of the particular goals set for a specific problem. In this way it also contributes to the desirable transparency in the obtained results as the description of a vessel's performance it offers is directly identifiable. This approach is well suited to and compatible with the broad multiple criteria methodology. Finally, it is realistic, particularly for concept-stage decision making investigations where detailed information may not be available. In this context the concise and easily identifiable description of alternative designs is both realistic and of practical use for potential users of the model such as designers and operators.

9.4.3. Fuzzy sets (alternatively utility functions) offer a number of advantages in the context of the high-speed ferry decision making problem. They allow the quantification of natural language terms which are included in the definitions of the primary goals. At the same time they allow the uniform modelling and normalisation of goals and attributes which are of significantly different nature. This is important in the context of the primary attribute multiple criteria approach. It also offers a way to implicitly address the issue of weightings which often is a source of dispute within the application of such methods. By combining these features the use of fuzzy sets facilitates the direct definition of an overall ranking index (or quality function) to be used for the comparison of competing designs.

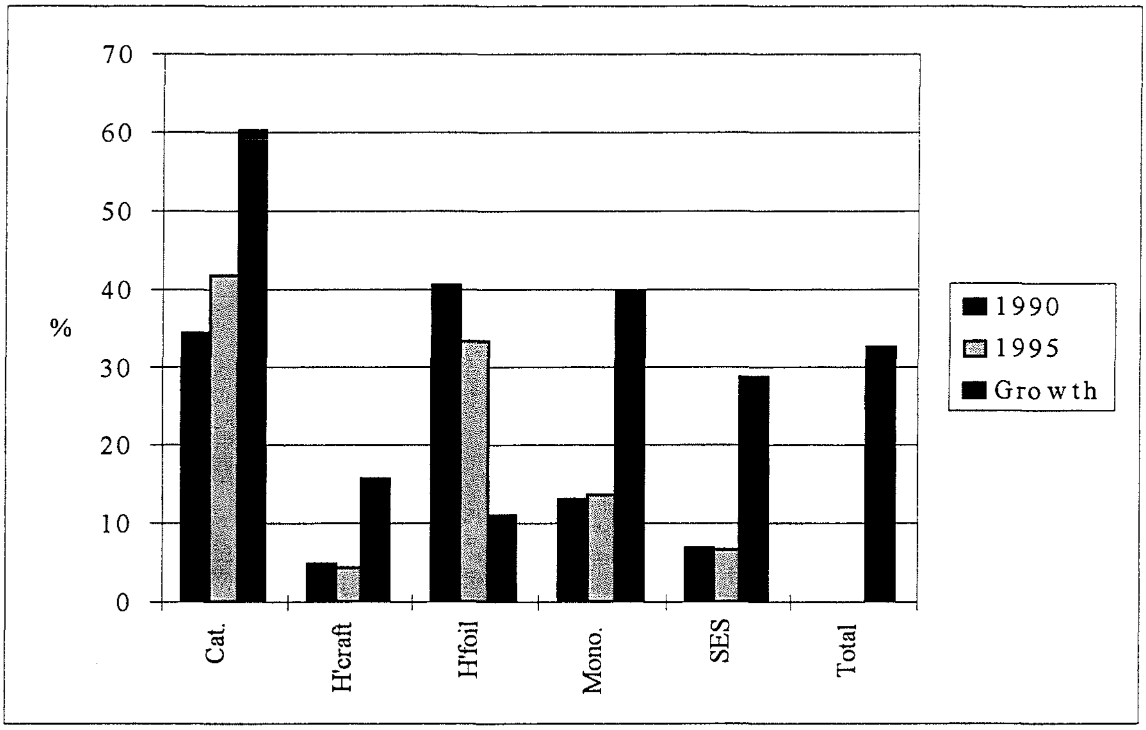
9.4.4. A comprehensive sensitivity analysis, which is important for high-speed ferry selection, can be adequately and efficiently performed within the developed decision making methodology. Such a systematic sensitivity analysis allows the selection of the most robust design through the use of an appropriately defined signal-to-noise ratio as the final criterion. The concept of design robustness is addressed by applying the Taguchi-type approach.

9.4.5. Taguchi's method offers a useful tool which is well suited for the high-speed ferry decision making model. It is efficient and allows a rapid but comprehensive investigation of concept design and decision making problems. This is possible through the use of orthogonal arrays which facilitates the systematic generation and investigation of alternative designs and scenarios efficiently within an overall integrated algorithm. Furthermore it produces results in a highly transparent form.

9.4.6. It would be worthwhile to investigate the potential and implications of applying a cost-benefit analysis within the decision making framework. Such an analysis is highly compatible with the developed primary attribute approach and might require only minor restructuring. This would involve a different grouping of the assembled attributes by separating the costing attributes from the remaining performance attributes, which would then indicate the benefit as defined in such analyses. Direct eliminations of unsatisfactory (or inefficient) designs at some appropriate stage of the decision making algorithm are possible with a cost-benefit analysis. The philosophy of such analyses has the additional advantage of being well suited to the considerations of real life decision making problems as encountered by operators and designers.

9.4.7. The developed decision making framework offers the facility to investigate any high-speed ferry selection problem. Its structure and formulation of main characteristics are such that it can cope with designs of any hull type and configuration. It is simple to use and efficient as the overall methodology can be applied very rapidly. At the same time the obtained results are adequately comprehensive and reliable for the needs of concept-stage design and decision making, but also transparent and directly identifiable. The model would be strengthened by the inclusion of a more sophisticated search algorithm in its initial stages and such an approach would be worthy of further investigation.

Figure 1.1: Fast Ferry Market Breakdown and Growth (Data from [1])



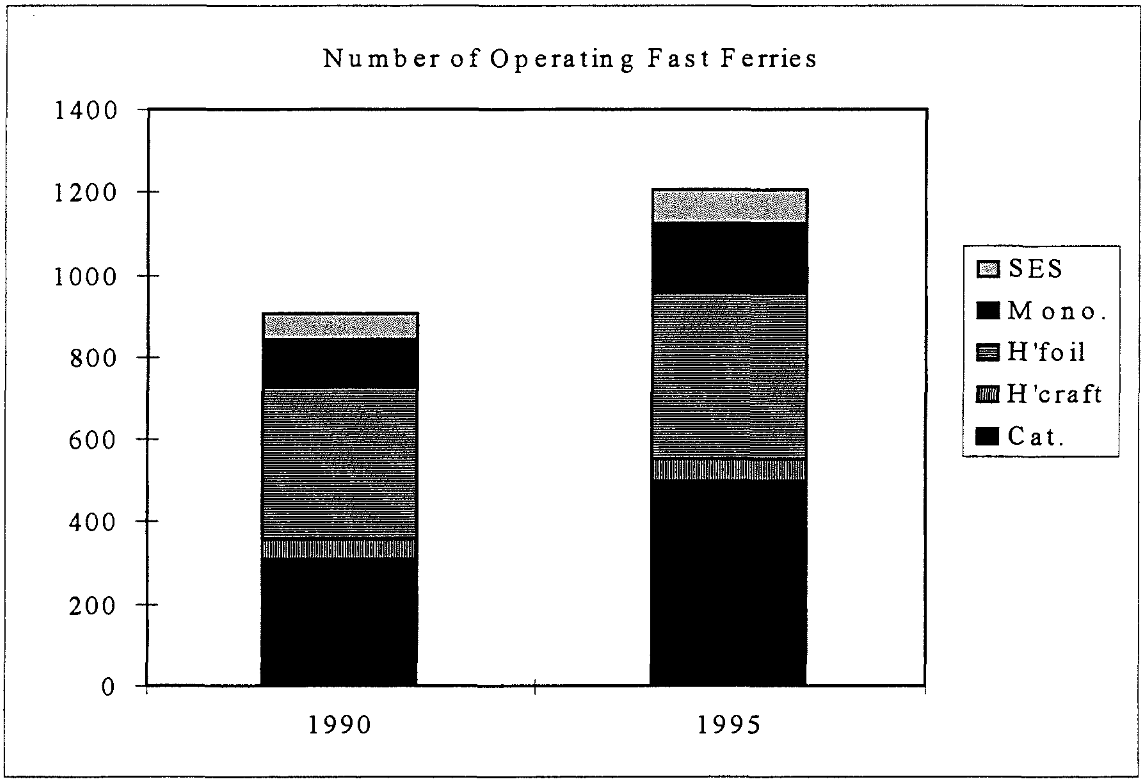


Figure 1.2: Global Model (Overview)

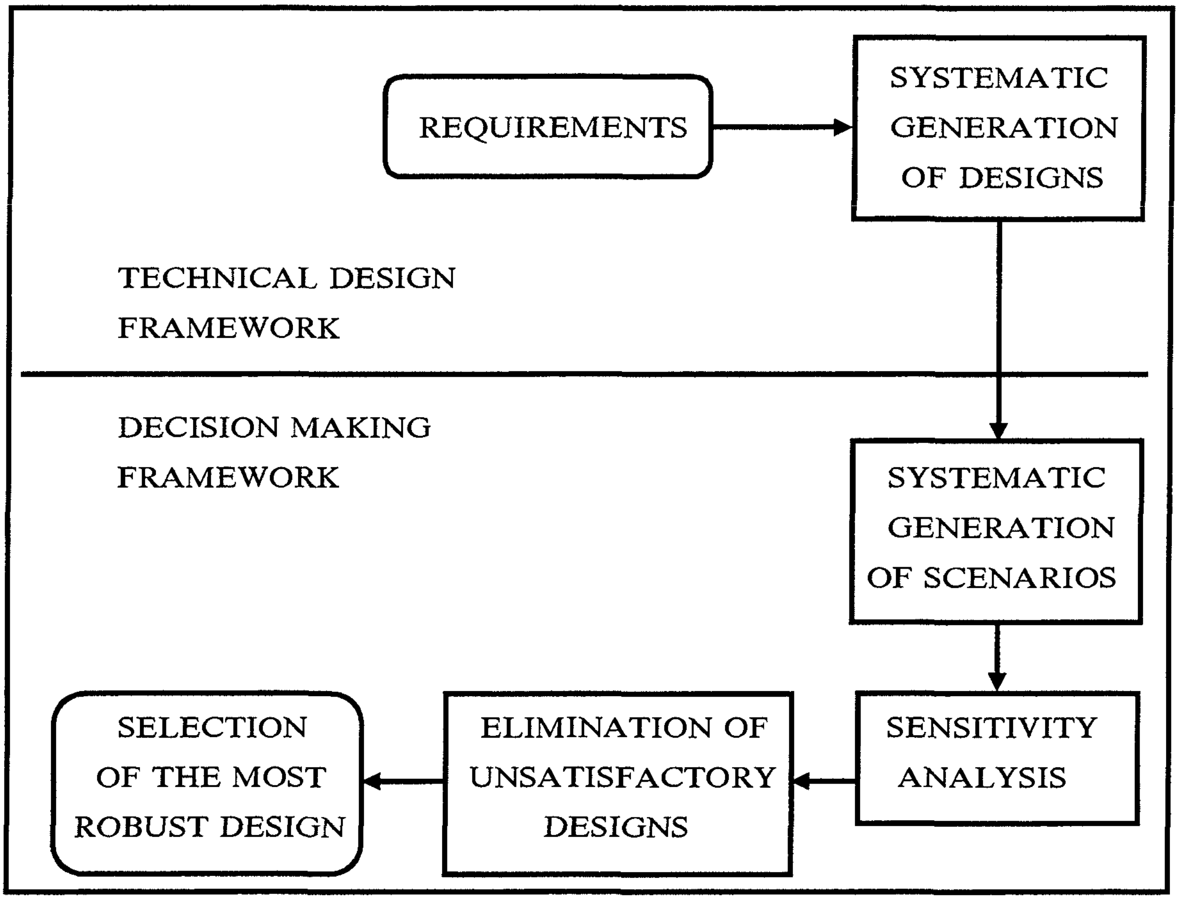
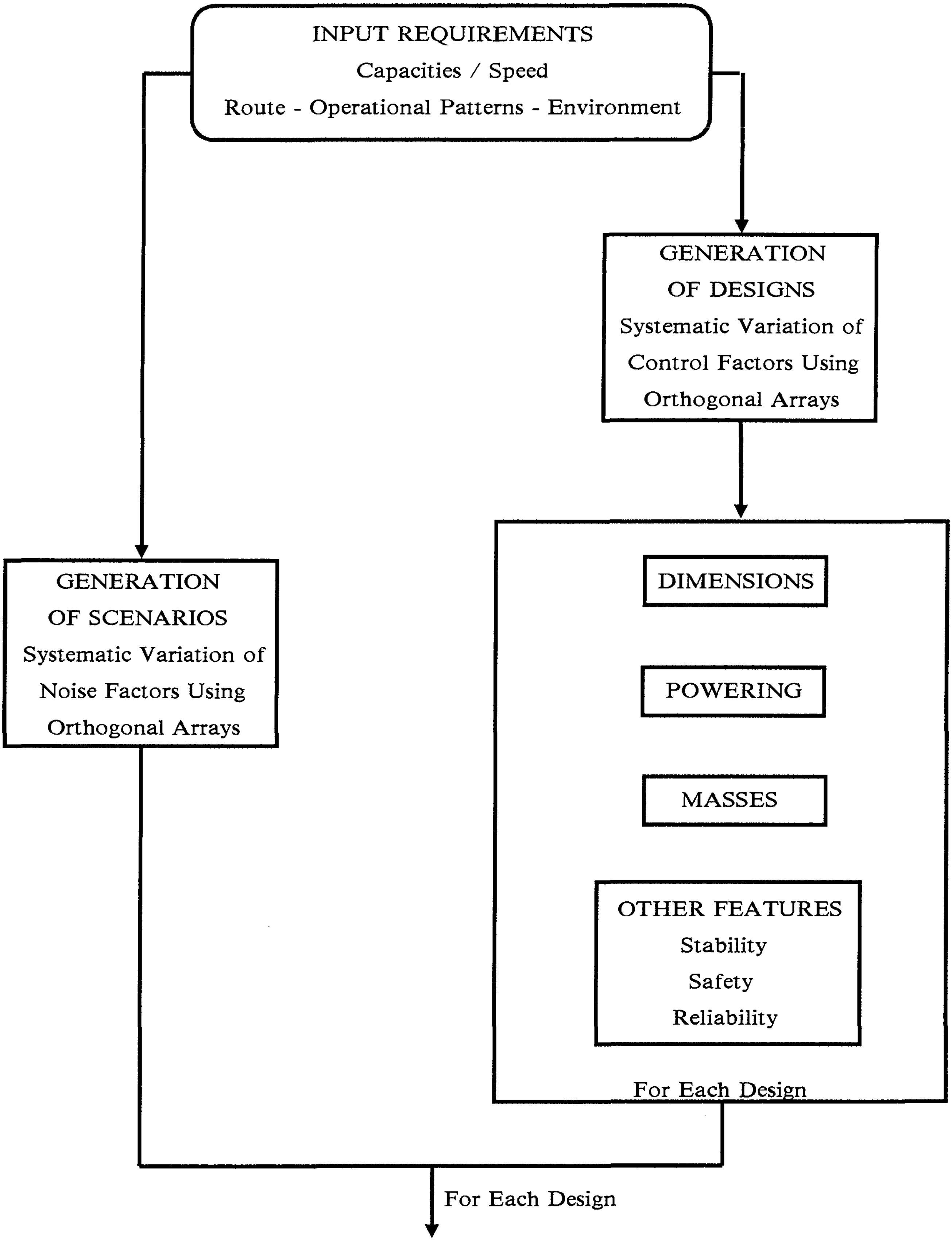


Table 3.2.1: Indicative Primary Attributes

DIMENSIONS
Possible changes due to level of quality of passenger accommodation/seating.
BUILDING/REPAYMENT COST
Say annual.
FUEL COST
Say annual - based on simulated voyages.
SEAKEEPING ATTRIBUTES
1. Structural integrity. 2. Safety. 3. Power increase for given speed - Fuel. 4. Operational limits - Availability. 5. Passenger comfort/satisfaction ?

Figure 4.3.1: Overall Algorithm Flowpath



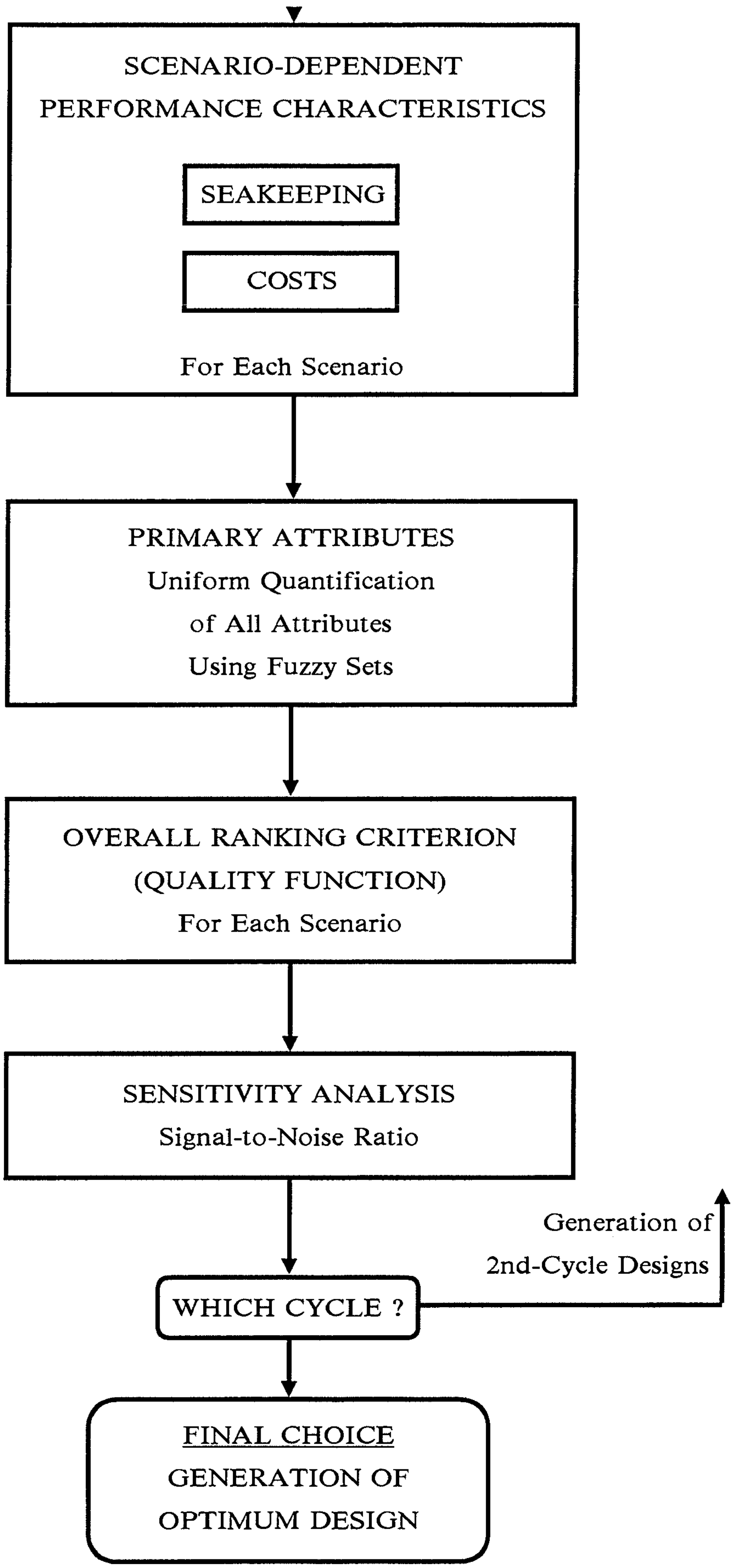

SCENARIO-DEPENDENT
PERFORMANCE CHARACTERISTICS
SEAKEEPING
COSTS
For Each Scenario
PRIMARY ATTRIBUTES
Uniform Quantification
of All Attributes
Using Fuzzy Sets
OVERALL RANKING CRITERION
(QUALITY FUNCTION)
For Each Scenario
SENSITIVITY ANALYSIS
Signal-to-Noise Ratio
Generation of
2nd-Cycle Designs
WHICH CYCLE ?
FINAL CHOICE
GENERATION OF
OPTIMUM DESIGN

Table 5.2.1: Size of the High-Speed Ferry Databases

VESSEL TYPE	Number of different vessel designs	Total number of all variants
Passenger-only monohulls	27	30
Passenger-only catamarans	63	96
Other multihulls (totals)	21	26
Vehicle/passenger monohulls	42	60
Vehicle/passenger catamarans	59	84
Other multihulls (totals)	26	29

Table 5.3.1: Dimensions Regression Formulae

	Passenger-only monohulls	Passenger-only catamarans
$A_P \rightarrow L_{WL} \times B$	$L_{WL} \times B = 146 + 1.86 \times 10^{-3} A_P^2$ $[R^2 = 0.99]$	$L_{WL} \times B = 138 + 0.910\ A_P$ $[R^2 = 0.76]$
$L_{WL} \rightarrow L_{OA}$	$L_{OA} = 1.16\ L_{WL}$	$L_{OA} = 1.13\ L_{WL}$
	Vehicle/passenger monohulls	Vehicle/passenger catamarans
$N_V \rightarrow A_V$	$A_V = 156 + 10.2\ N_V$ $[R^2 = 0.92]$	$A_V = 12.4\ N_V$ $[R^2 = 0.99]$
$(A_P, A_V) \rightarrow L_{WL} \times B$	$L_{WL} \times B = 121 + 0.272 A_P + 0.599 A_V$ $[R^2 = 0.98]$	$L_{WL} \times B = 471 + 0.545 A_P + 0.275 A_V$ $[R^2 = 0.80]$
$L_{WL} \rightarrow L_{OA}$	$L_{OA} = 1.13\ L_{WL}$	$L_{OA} = 1.14\ L_{WL}$

Table 5.3.2: Database Range

	N_P	N_V
Passenger-only monohulls	150 - 900	-
Passenger-only catamarans	50 - 650	-
Vehicle/passenger monohulls	400 - 1800	< 450
Vehicle/passenger catamarans	150 - 1500	< 400

Table 5.3.3: Typical Confidence Intervals for Dimensioning Regression Equations

Independent variables	Dependent variable	Confidence = 95%	Confidence = 50%
Passenger-only monohulls – LxB = f(A_P)			
120	166.3	154.9-177.7	163.0-169.6
180	214.8	206.0-223.5	212.2-217.2
240	263.2	250.7-275.7	259.6-266.8
Passenger-only catamarans – LxB = f(A_P)			
150	268.2	215.8-320.5	250.3-286.0
250	353.1	324.1-382.1	343.3-363.0
350	438.1	410.0-466.2	428.5-447.7
Vehicle/passenger monohulls – LxB = f(A_P,A_V)			
900, 1500	1316.2	1213.3-1419.2	1284.0-1348.6
1200, 2200	1700.1	1617.5-1782.7	1674.2-1726.0
1500, 3000	2121.8	1998.3-2245.4	2083.1-2160.6
Vehicle/passenger monohulls – A_V = f(N_V)			
150	1692.7	1493.7-1891.7	1629.4-1756.0
200	2204.9	2029.3-2380.5	2149.0-2260.8
250	2717.1	2495.0-2939.1	2646.4-2787.7
Vehicle/passenger catamarans – LxB = f(A_P,A_V)			
700, 1000	1127.6	994.7-1260.5	1083.7-1171.5
1000, 2000	1522.6	1314.0-1731.3	1453.7-1591.6
1300, 3000	1917.7	1567.6-2267.8	1801.9-2033.4
Vehicle/passenger catamarans – A_V = f(N_V)			
50	634.4	572.1-676.7	614.4-654.4
100	1246.1	1192.4-1299.8	1228.8-1263.4
150	1857.8	1791.6-1924.0	1836.5-1879.1

Figure 5.3.1: Flowpath for Initial Estimation of Main Dimensions - Monohulls

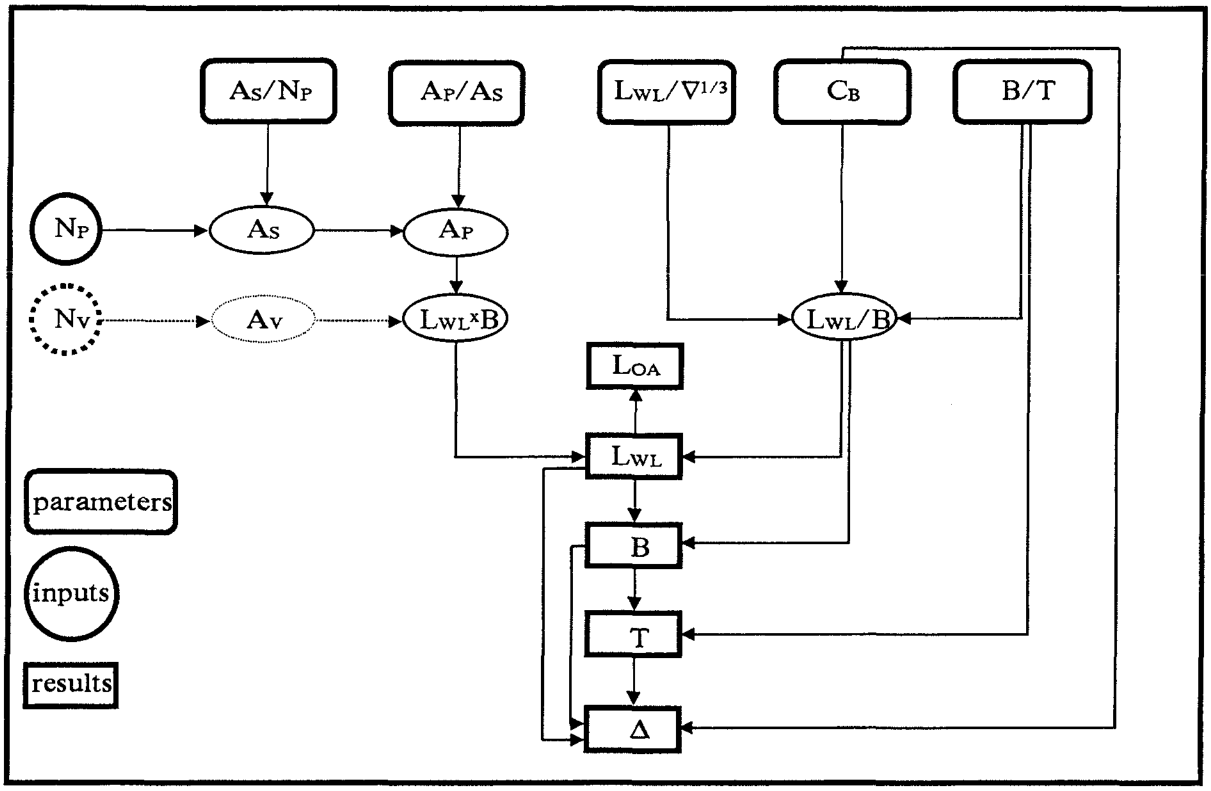


Figure 5.3.2: Flowpath for Initial Estimation of Main Dimensions - Catamarans

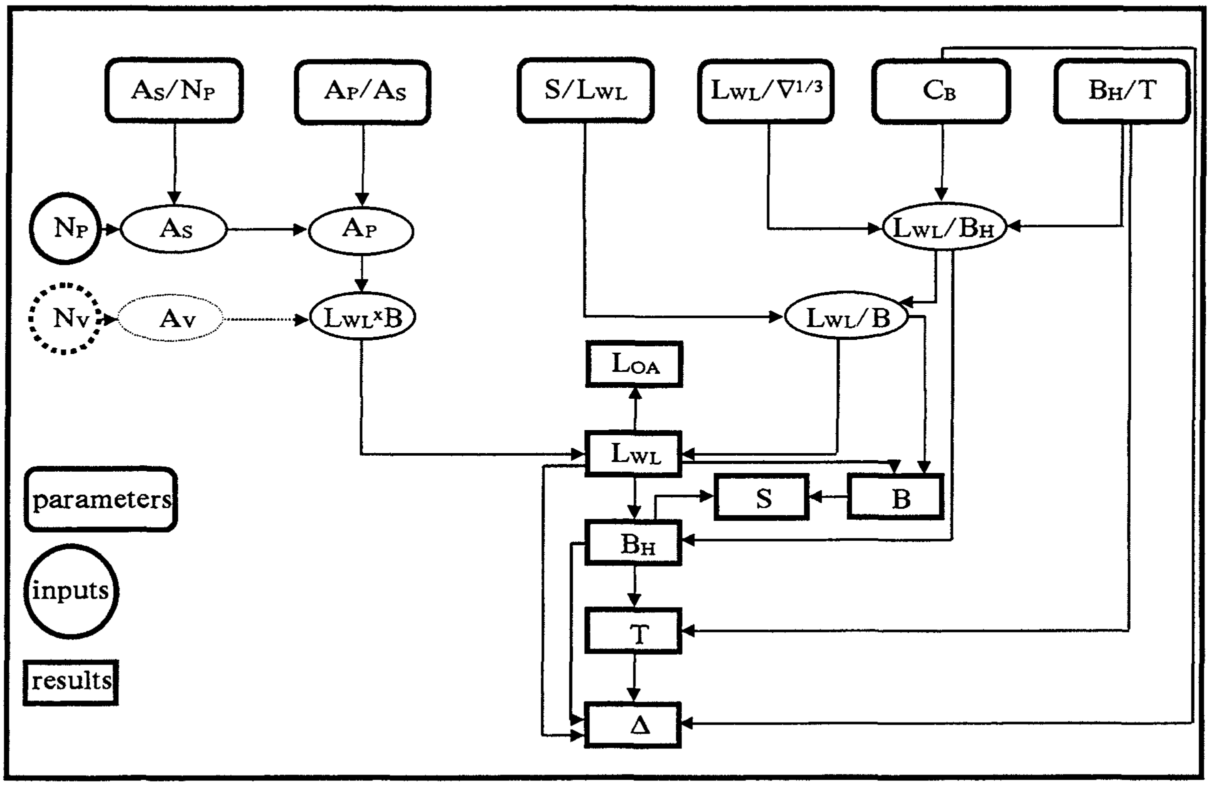
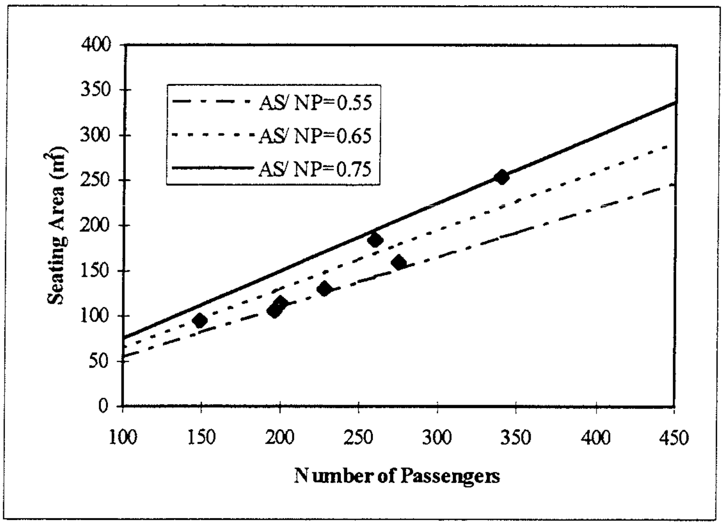
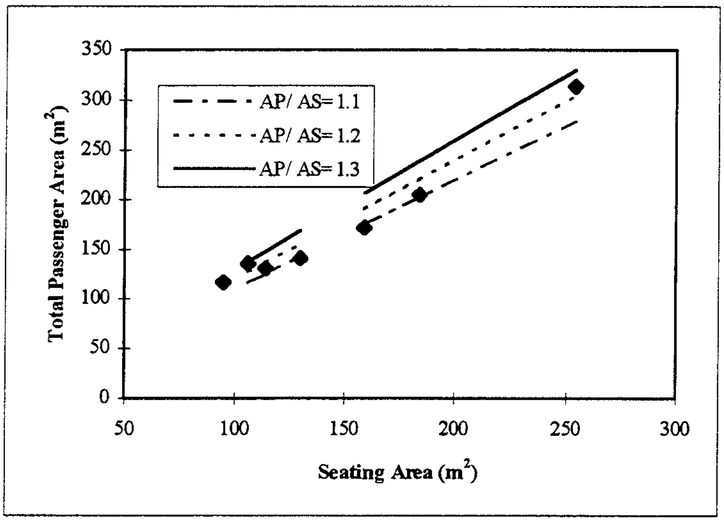


Figure 5.3.3: Dimensions Data Plots - Passenger-Only Monohulls





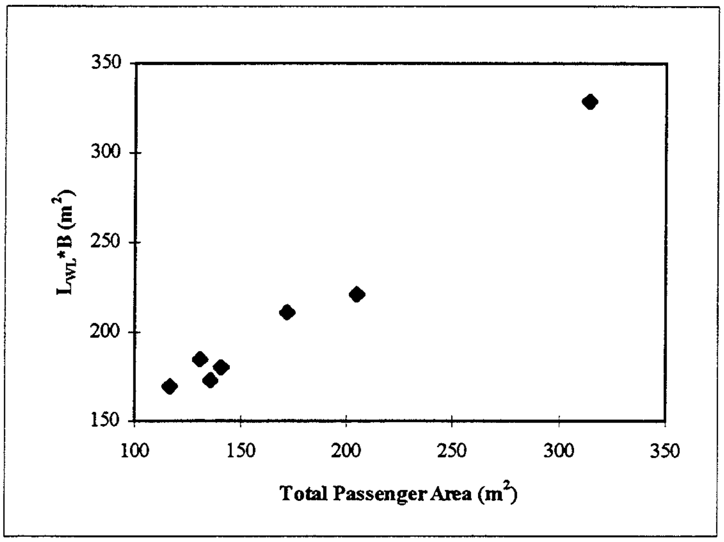
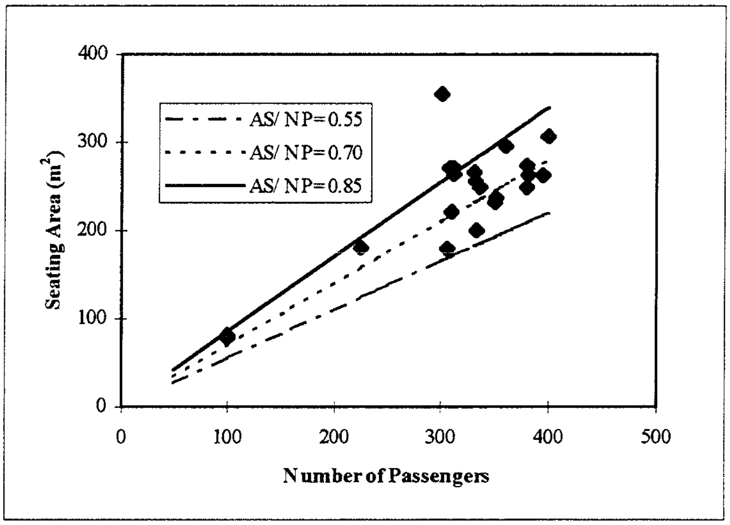
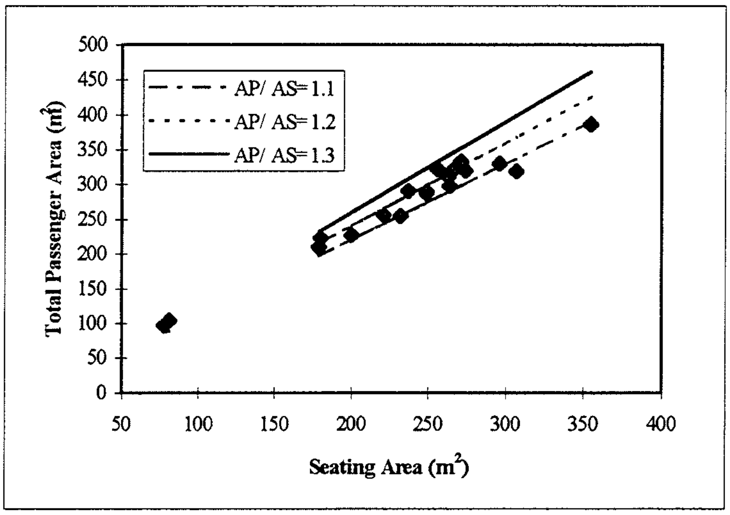


Figure 5.3.4: Dimensions Data Plots - Passenger-Only Catamarans





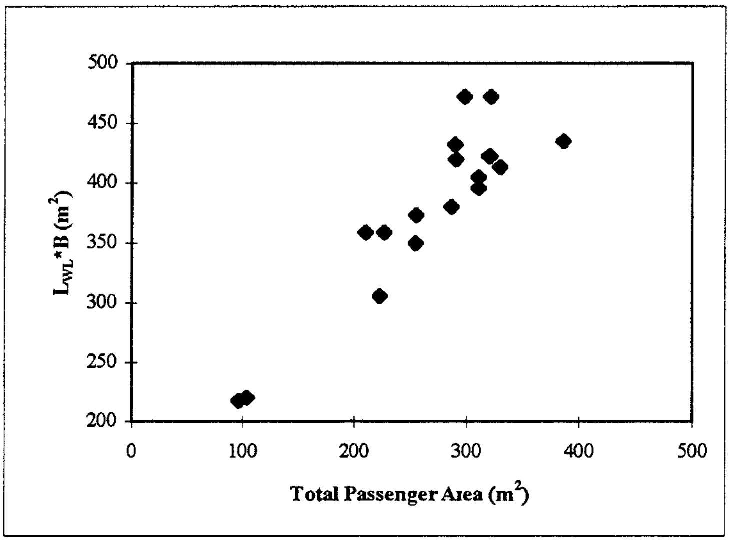
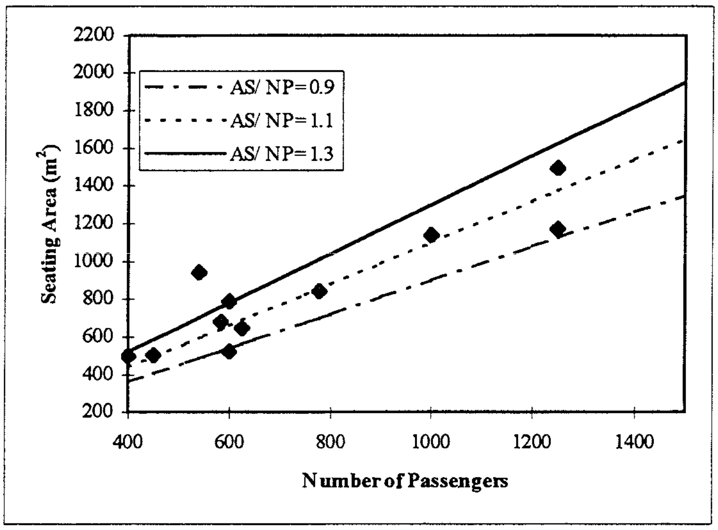
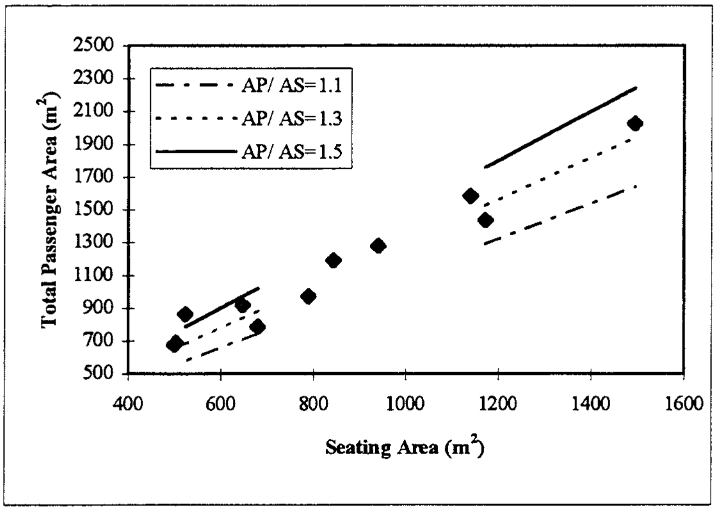


Figure 5.3.5: Dimensions Data Plots - Vehicle/Passenger Monohulls





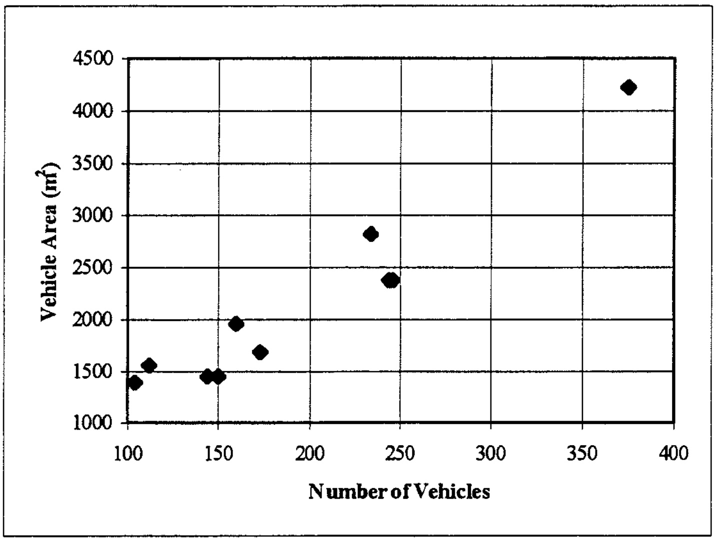
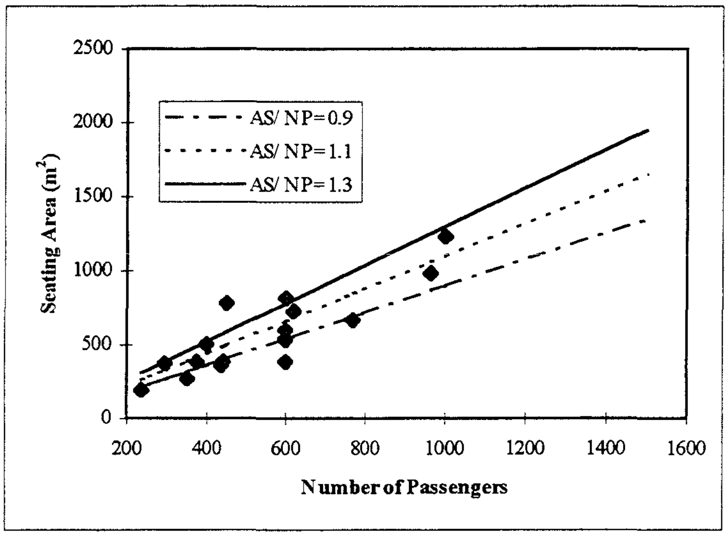
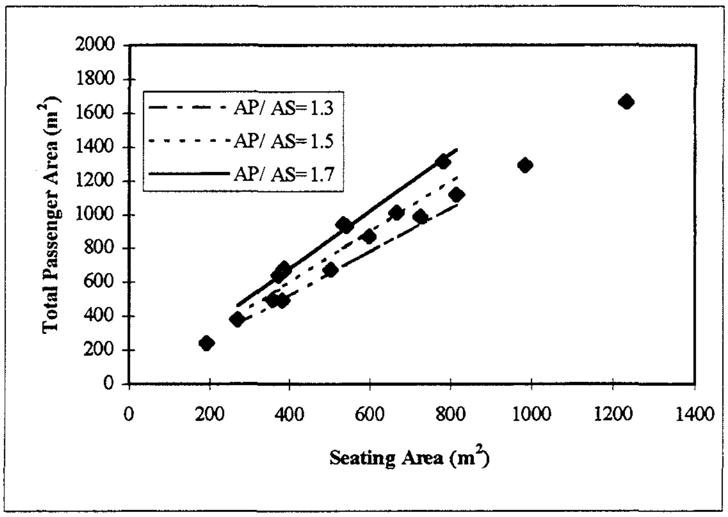


Figure 5.3.6: Dimensions Data Plots - Vehicle/Passenger Catamarans





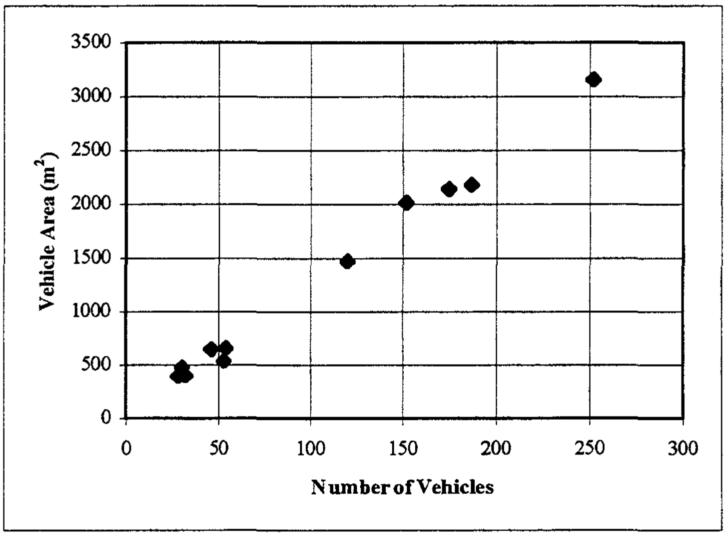


Figure 5.4.1: Waterjet Efficiency

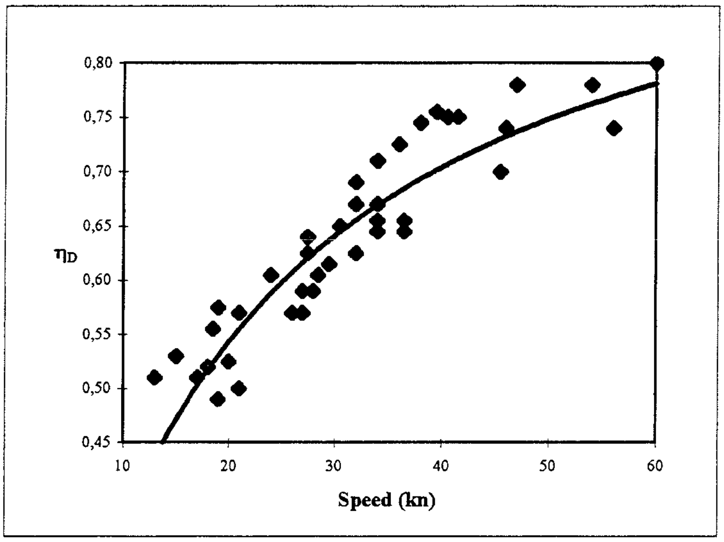


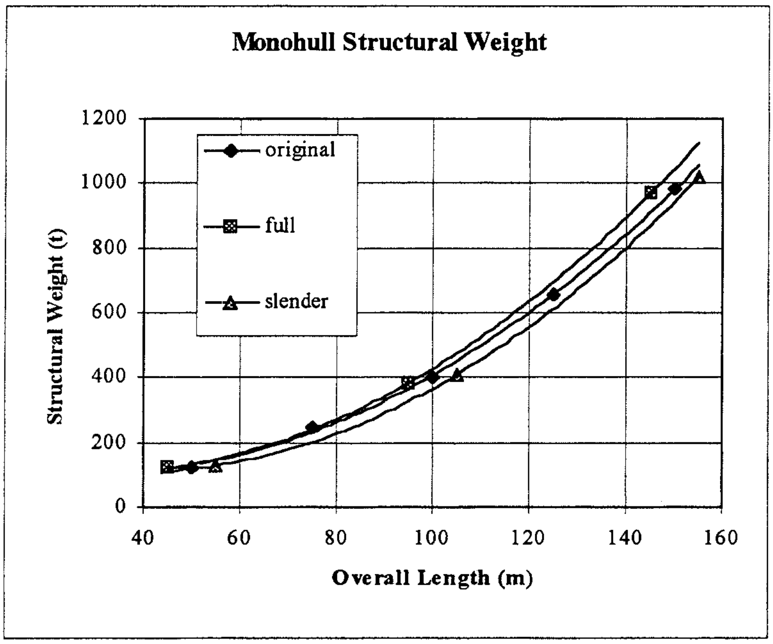
Table 5.5.1: Machinery Mass - Regression Equations

Diesel engines	W_D [t] = 5.75 (P/n [kW/rpm])$^{0.9}$
Gas turbines - Dry weight Total module weight	W_{GT} [kg] = 0.55 P[kW]$^{0.9}$ W_{GTM} [t] = 5.0 + 0.6 P[MW]$^{0.9}$
Gearboxes	W_{GB} [kg] = 350 P[MW]$^{1.25}$
Waterjets - Booster Steerable Units	W_{WJ} [kg] = 0.25 P[kW]$^{1.1}$ W_{WJ} [kg] = 0.37 P[kW]$^{1.1}$

Table 6.2.2: Machinery Cost - Regression Equations

Diesel engines	C_D [k $US] = 0.253 P[kW]
Gas turbines	C_{GT} [k $US] = 2x10^{-10} P[kW]^3 - 10^{-5} P[kW]^2 + 0.411 P[kW]
Gearboxes	C_{GB} [k $US] = -3x10^{-7} P[kW]^2 + 0.0237 P[kW]
Waterjets	C_{WJ} [k $US] = 3.07 P[kW]$^{0.6}$

Figure 5.5.1: Parametric Hull Mass Investigations



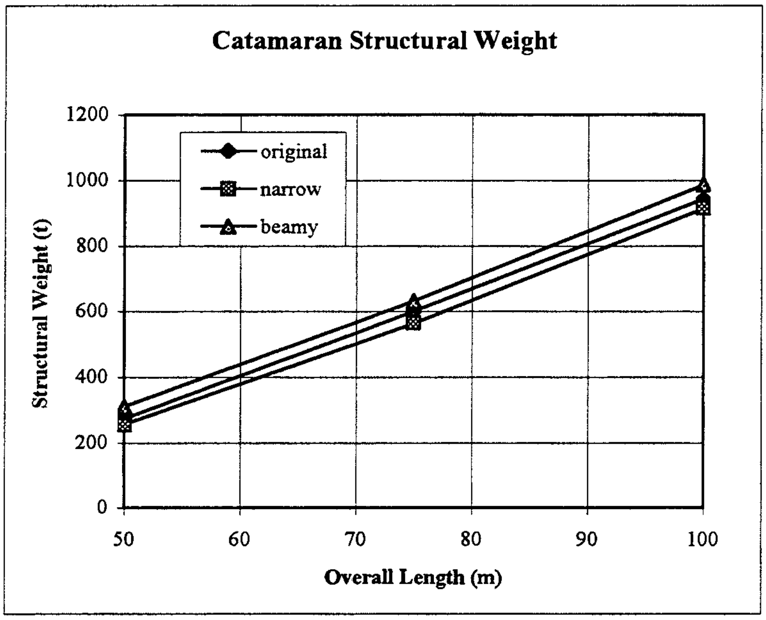


Figure 5.5.2: Diesel Engine Mass

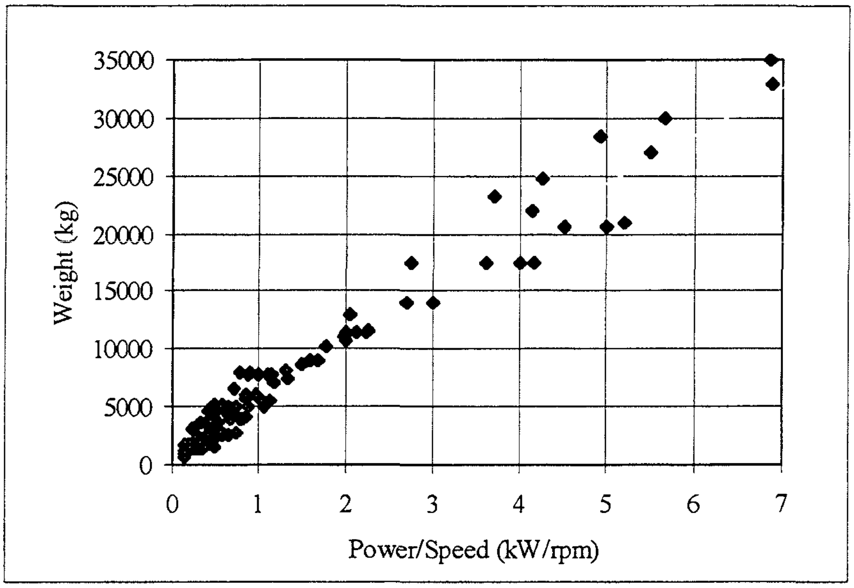


Figure 5.5.3: Gas Turbine Mass

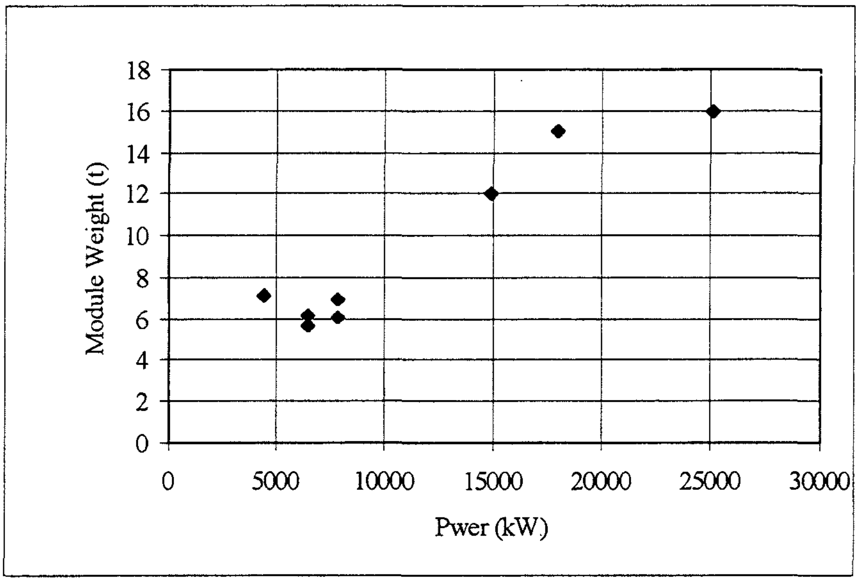


Figure 5.5.4: Gearbox Mass

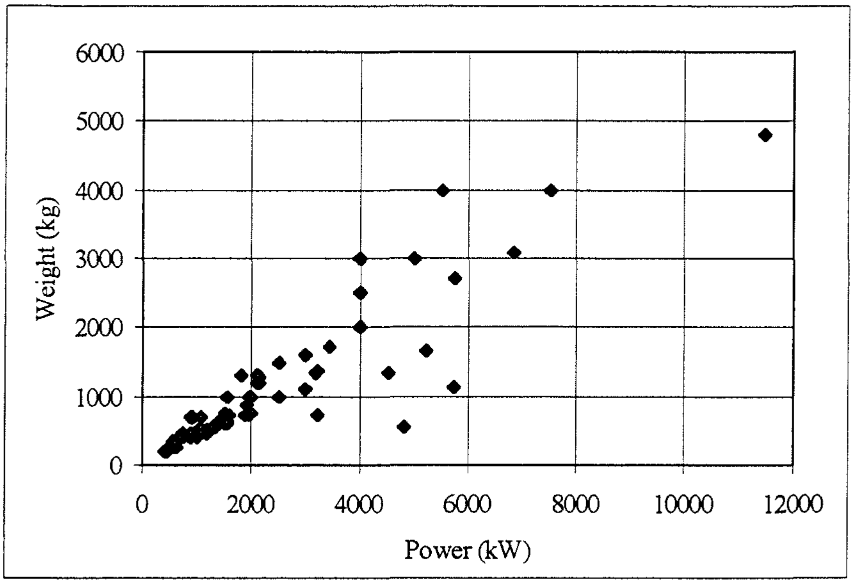


Figure 5.5.5: Waterjet Mass

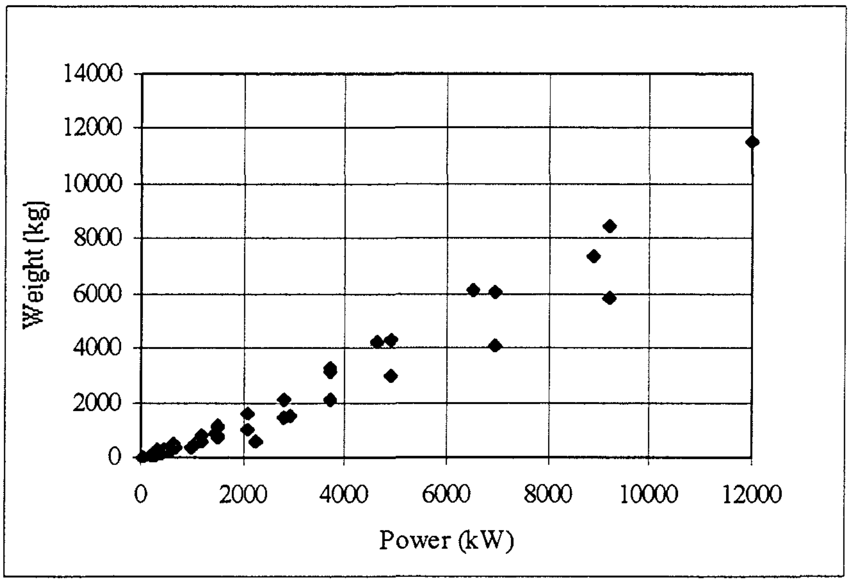


Table 5.7.1: Design Parameters for Example Passenger-Only Vessels

Parameter	Monohull	Catamaran
A_S/N_P (m^2)	0.60	0.65
A_P/A_S	1.15	1.20
S/L_{WL}	-	0.22
$L_{WL}/\nabla^{1/3}$	7.2	9.4
B/T (B_H/T for cat.)	5.4	2.0
C_B	0.35	0.40
N_P	350	350
V_S (kn)	33	33

Table 5.7.2: Main Characteristics of Example Passenger-Only Vessels

	Monohull	Catamaran
L_{OA} (m)	40.33	41.08
L_{WL} (m)	35.38	36.04
B (m)	7.19	10.72
B_H (m)	-	2.80
T (m)	1.33	1.40
S (m)	-	7.93
Δ (t)	122	115
P (kW)	4400	4200

Table 5.7.3: Design Parameters for Example Vehicle/Passenger Vessels

Parameter	Monohull	Catamaran
A_S/N_P (m^2)	0.95	1.10
A_P/A_S	1.20	1.40
S/L_{WL}	-	0.24
$L_{WL}/\nabla^{1/3}$	7.7	9.0
B/T (B_H/T for cat.)	5.4	2.2
C_B	0.35	0.40
N_P	620	620
N_V	160	160
V_S (kn)	36	36

Table 5.7.4: Main Characteristics of Example Vehicle/Passenger Vessels

	Monohull	Catamaran
L_{OA} (m)	98.92	78.26
L_{WL} (m)	86.78	68.65
B (m)	15.95	22.30
B_H (m)	-	5.83
T (m)	2.95	2.77
S (m)	-	16.48
Δ (t)	1467	910
P (kW)	33000	23000

Figure 6.2.1: Initial Building Cost Estimation Based on Ship Length

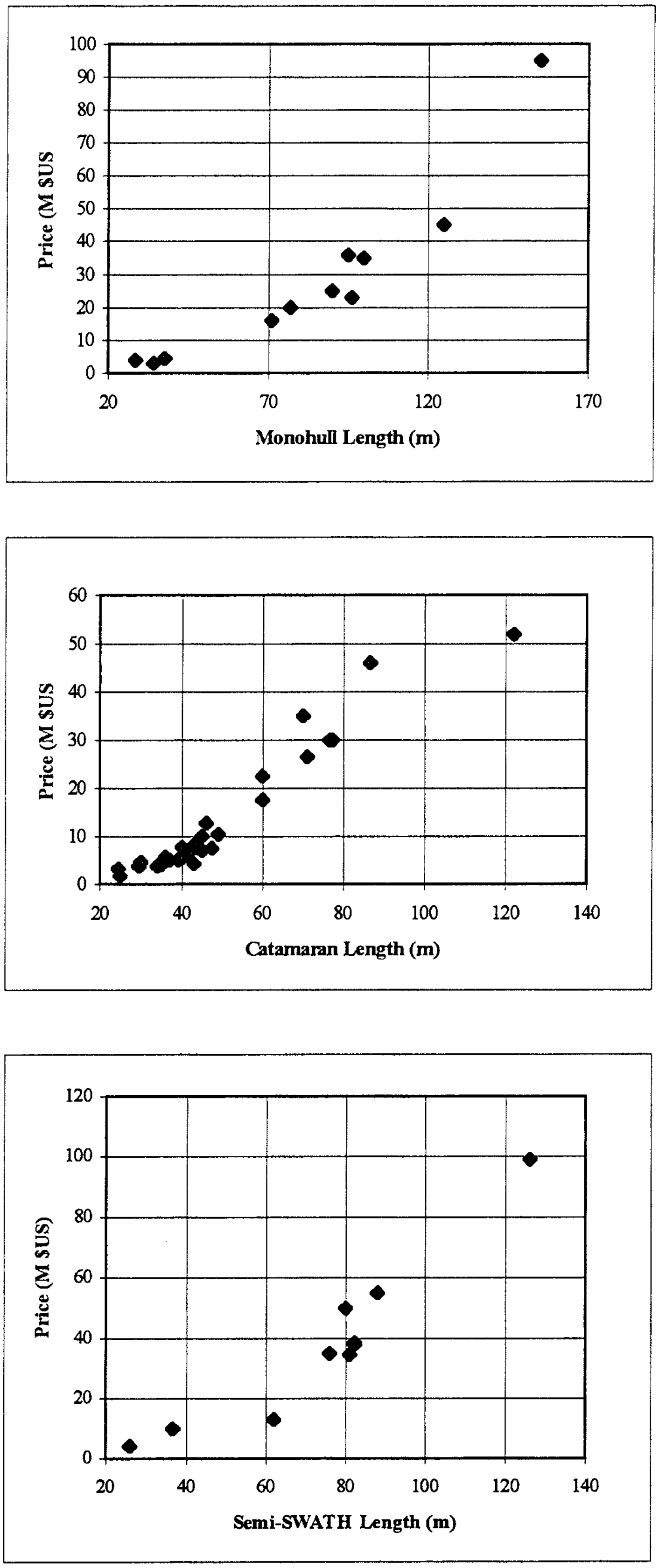
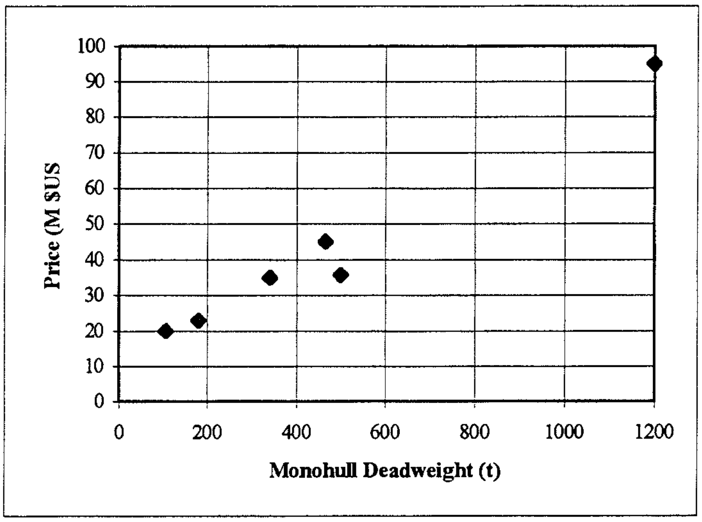
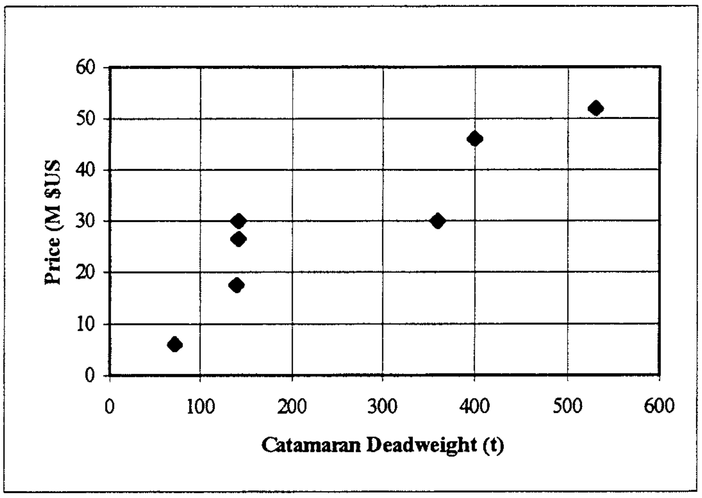


Figure 6.2.2: Initial Building Cost Estimation Based on Deadweight





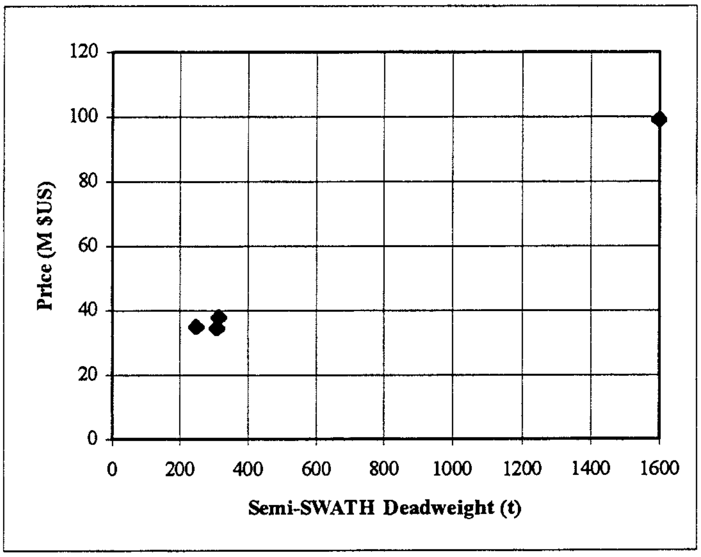


Figure 6.2.3: Initial Building Cost Estimation Based on Installed Power

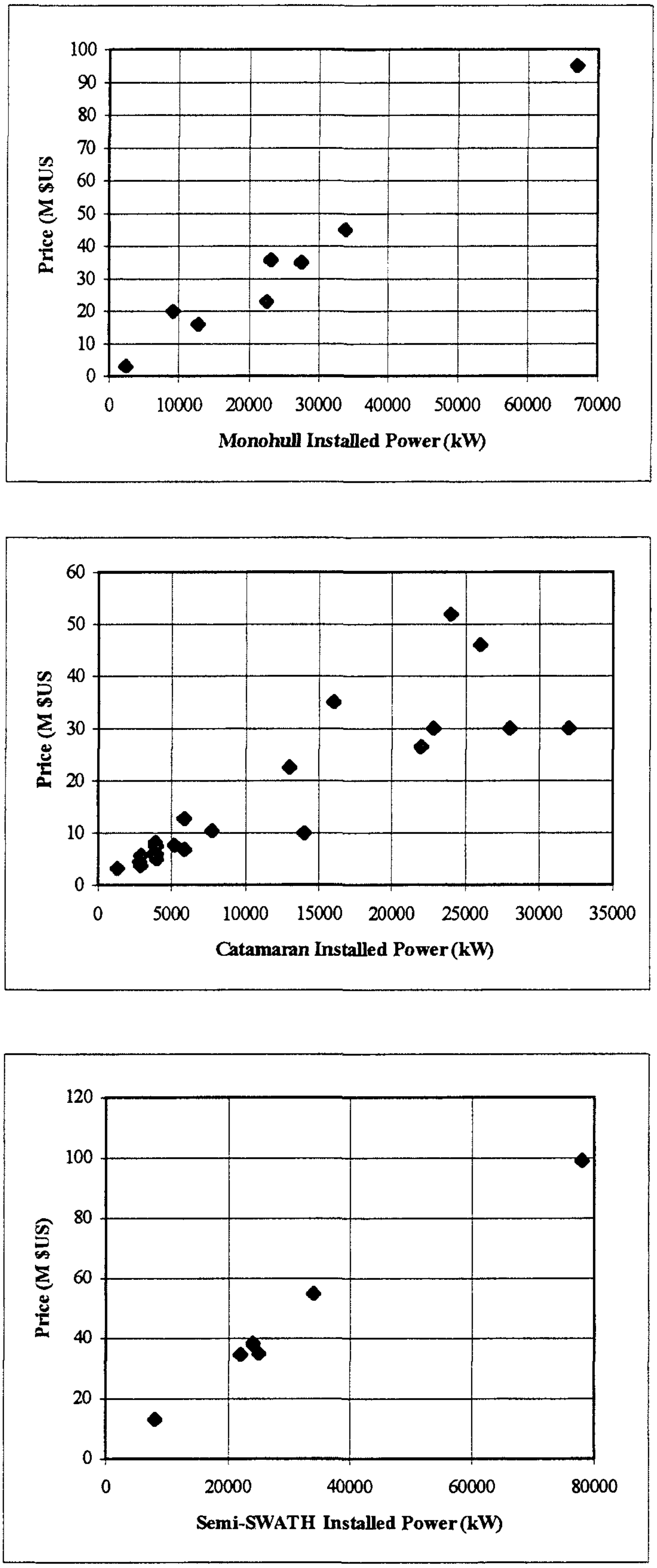
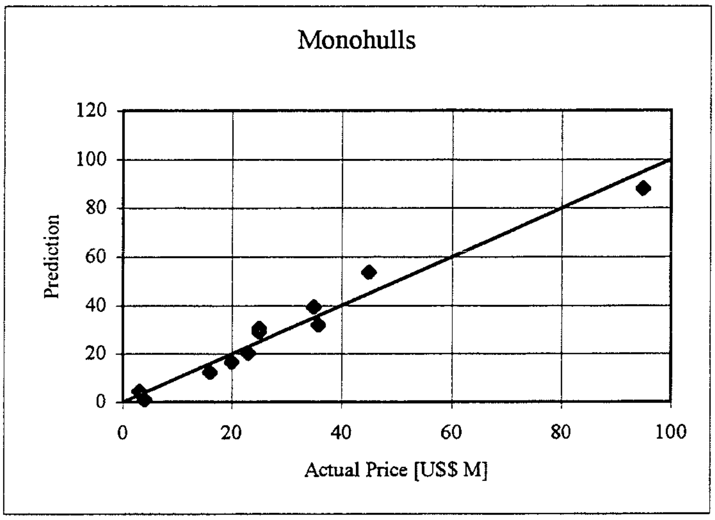
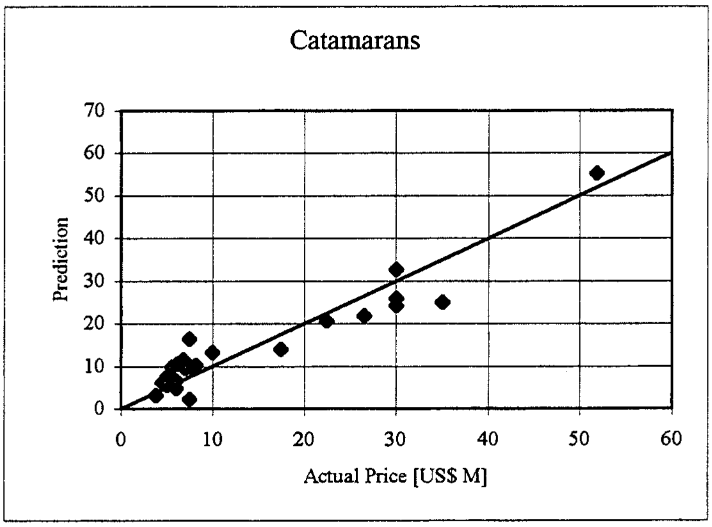


Figure 6.2.4: Initial Building Cost Estimation - Multi-Parameter Regressions





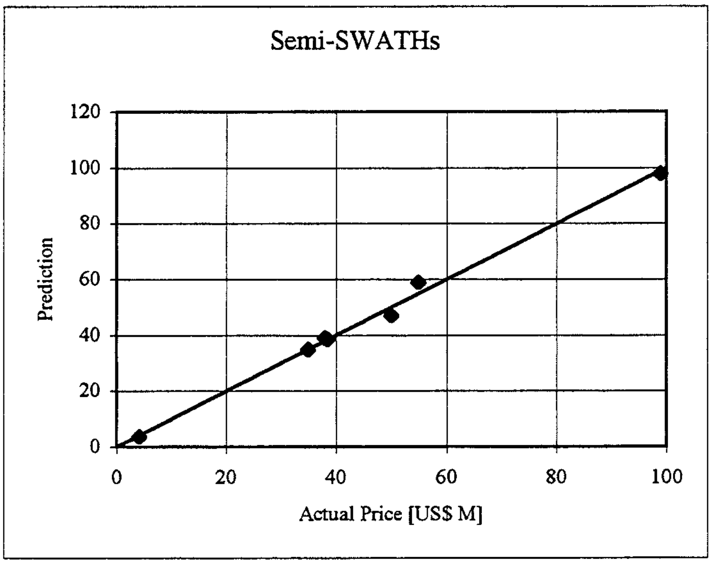


Table 6.2.1: Typical Confidence Intervals for Costing Regression Equations

Independent variables	Dependent variable	Confidence = 95%	Confidence = 50%
Monohulls – Building cost = f(N_P,N_V,V_S)			
450, 50, 35	16.5	9.9-23.2	14.5-18.6
650, 160, 35	32.1	25.8-38.5	30.2-34.1
800, 180, 38	39.9	34.0-45.9	38.1-41.8
1250, 250, 38	53.6	44.7-62.5	50.9-56.3
Catamarans – Building cost = f(N_P,N_V,V_S)			
300, 0, 35	5.1	2.7-7.5	4.3-5.9
450, 0, 36	10.6	8.0-13.2	9.7-11.5
450, 50, 40	19.7	17.5-21.8	18.9-20.4
620, 150, 36	39.1	34.5-43.6	37.5-40.6
Semi-SWATHs – Building cost = f(N_P,N_V,V_S)			
450, 120, 42	31.0	26.6-35.4	29.5-32.5
620, 160, 36	40.6	35.7-45.4	38.9-42.2
800, 200, 40	54.2	48.3-60.2	52.2-56.3
1500, 350, 40	100.8	88.7-112.8	96.7-104.8

Figure 6.2.5: Diesel Engine Initial Cost

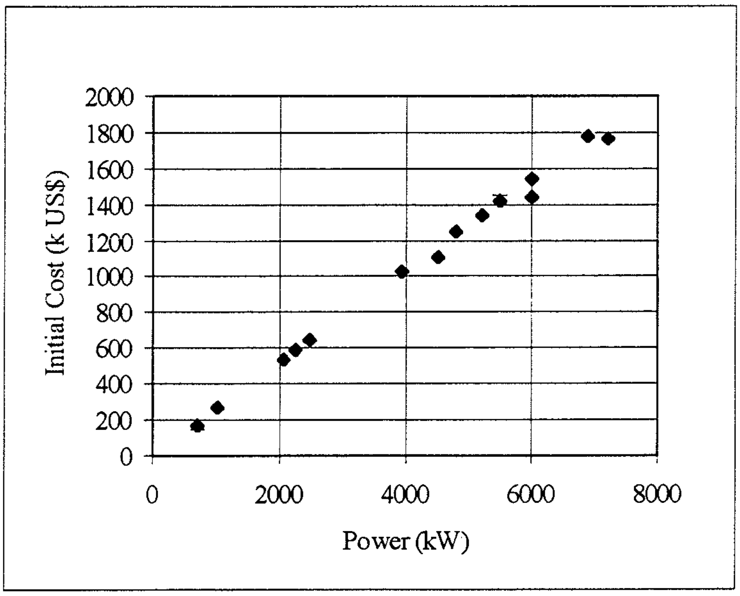


Figure 6.2.6: Gas Turbine Initial Cost

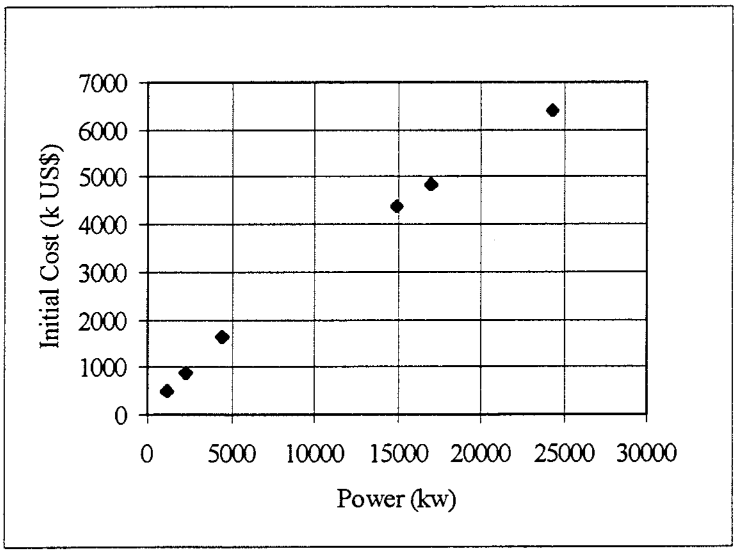


Figure 6.2.7: Gearbox Initial Cost

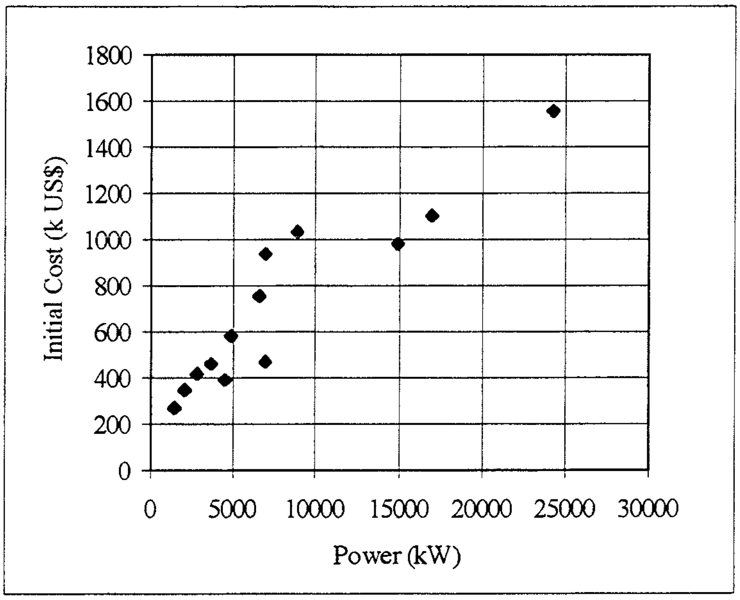


Figure 6.2.8: Waterjet Initial Cost

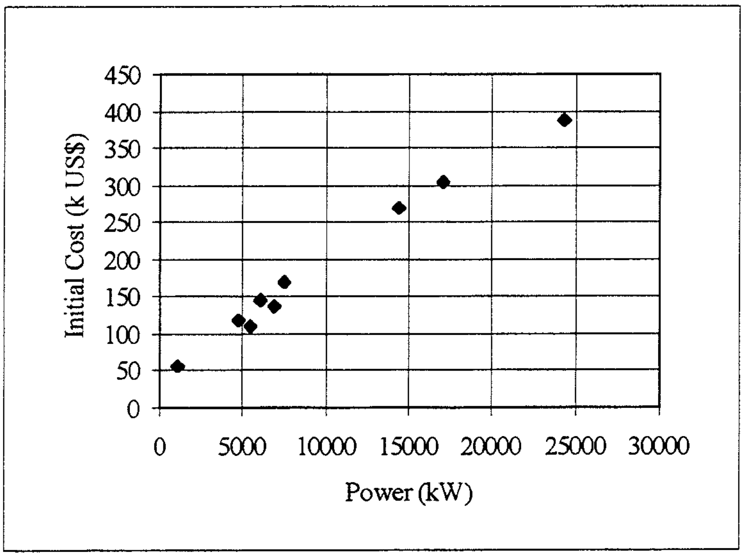


Figure 7.2.1: Definition of Seakeeping Performance Attributes

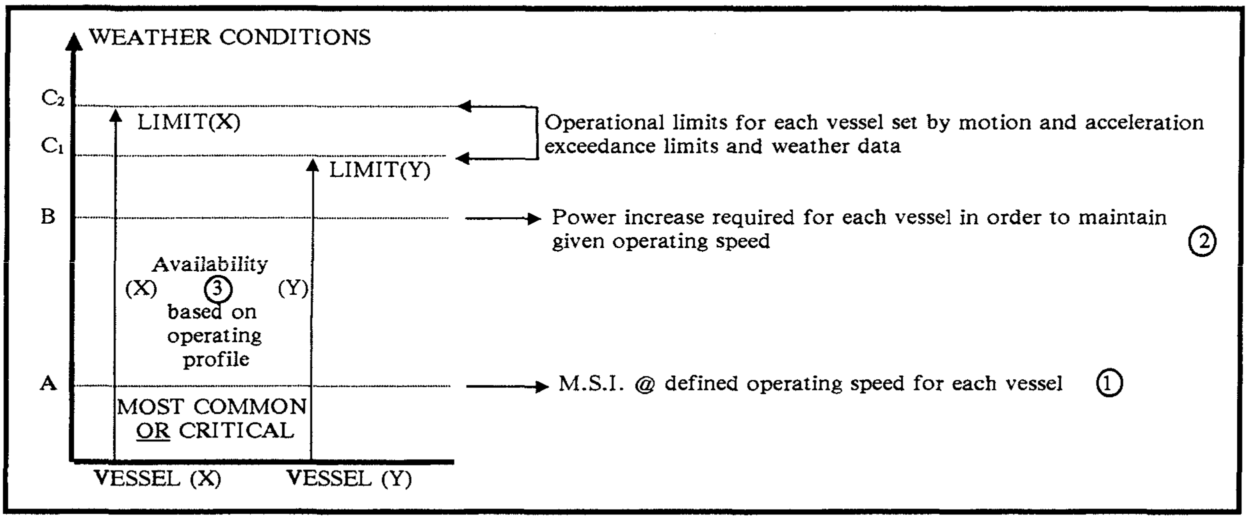


Figure 7.2.2: Selection of Primary Attributes

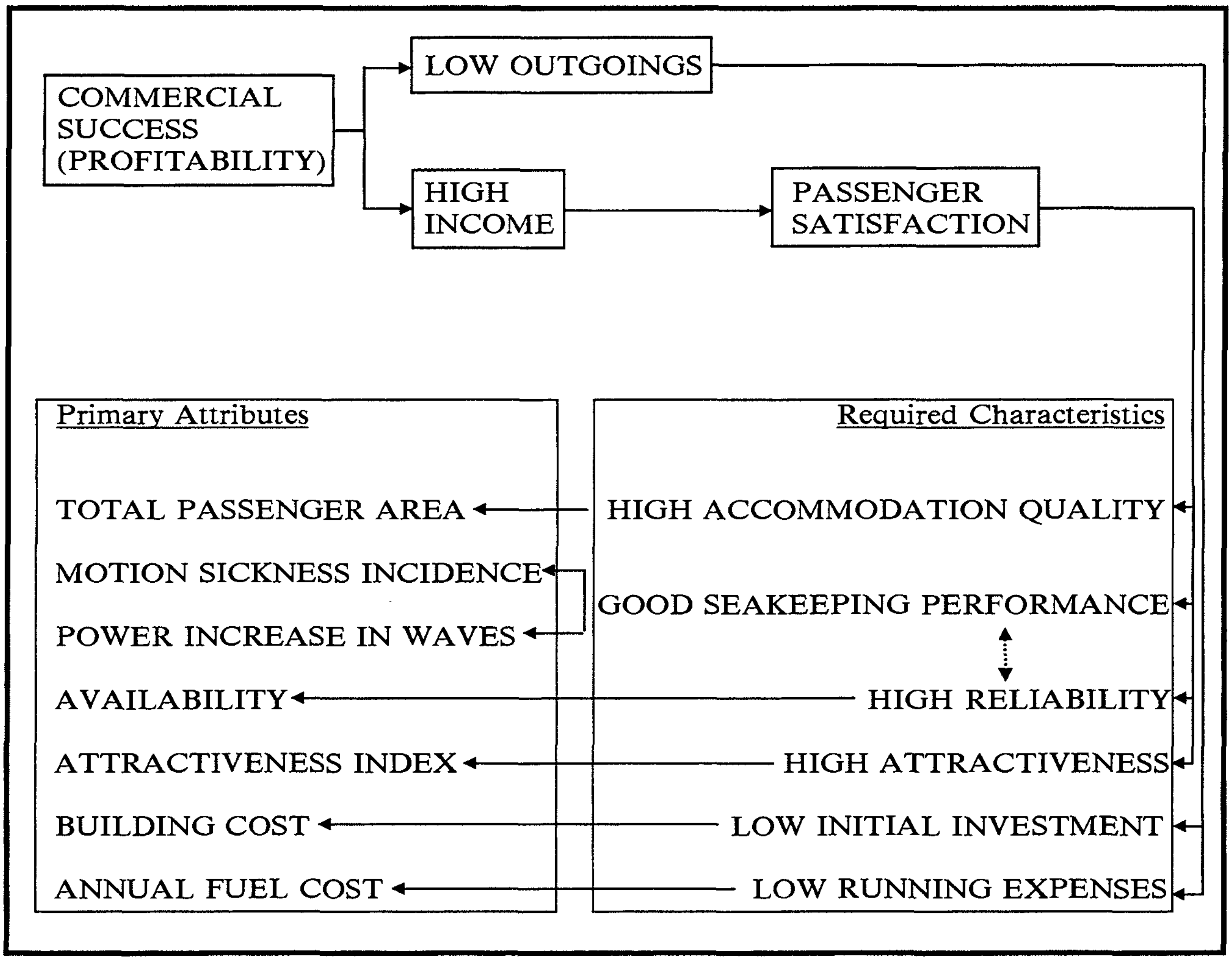


Figure 7.3.1: Parametric Variations of Speed and Crossing Distance (Indicative)

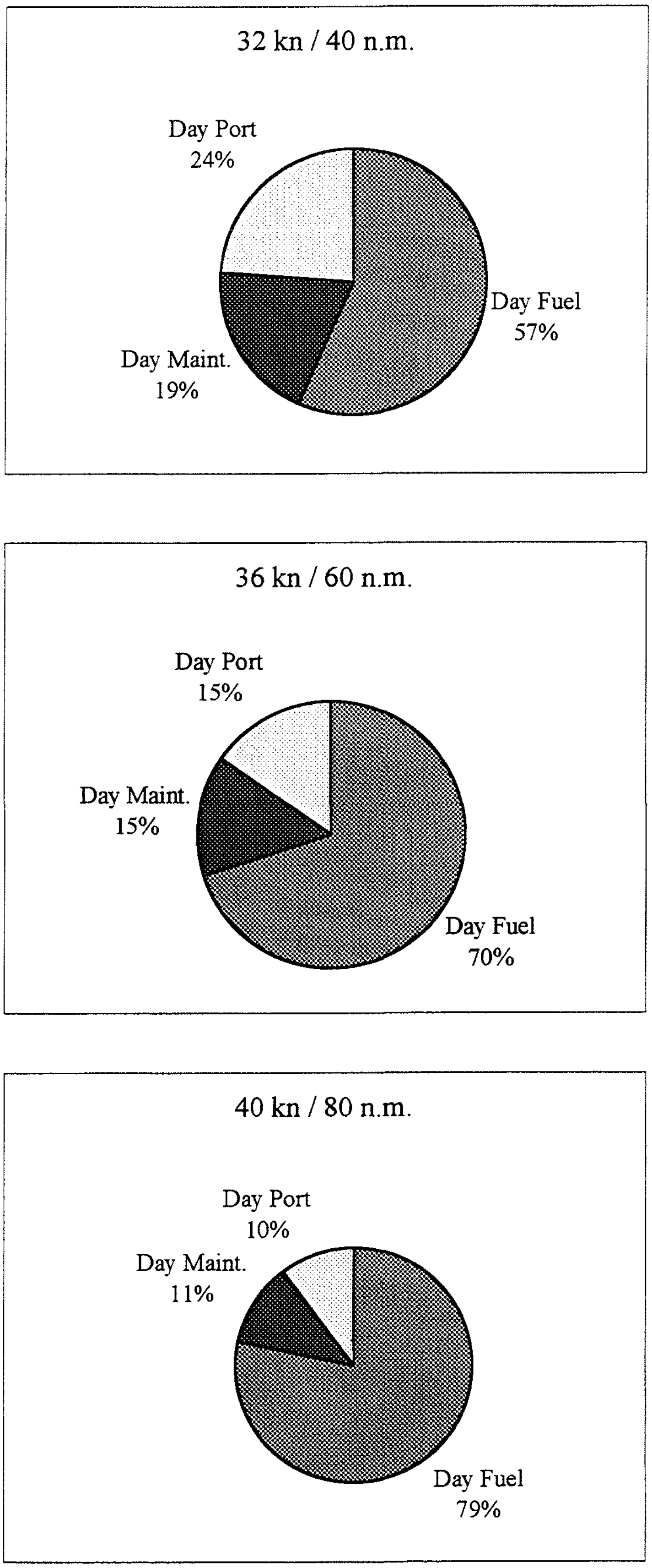
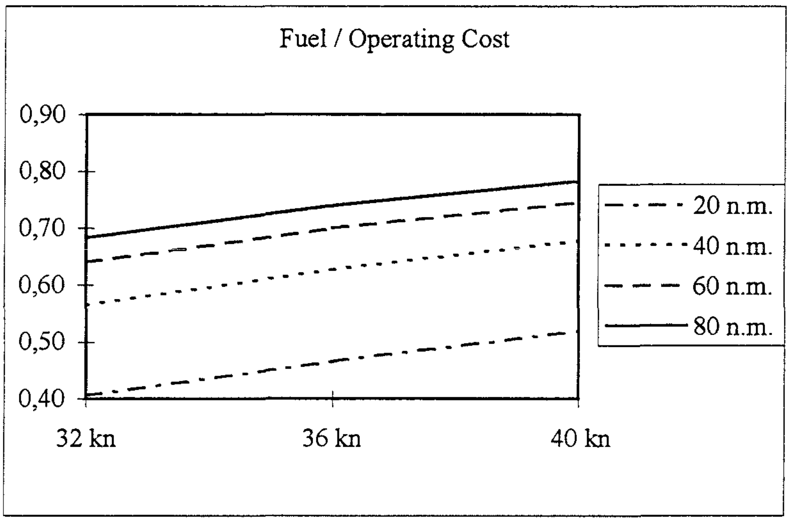
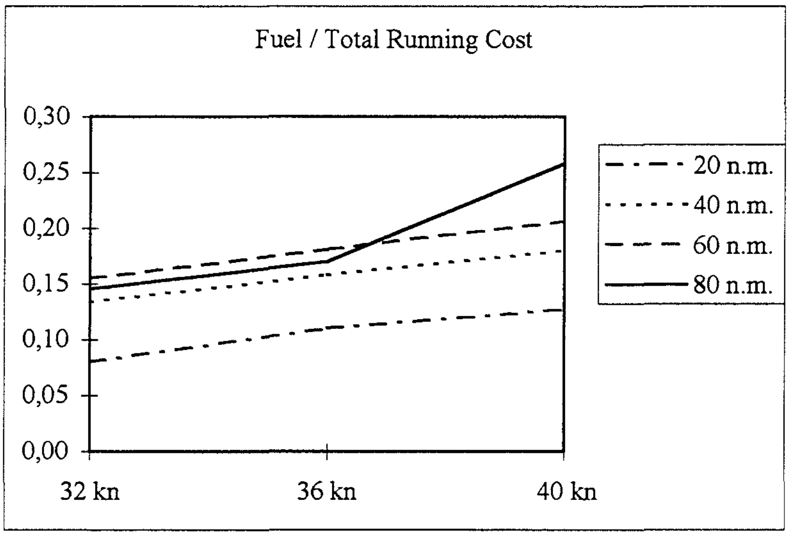


Figure 7.3.2: Effect of Parametric Variations of Speed





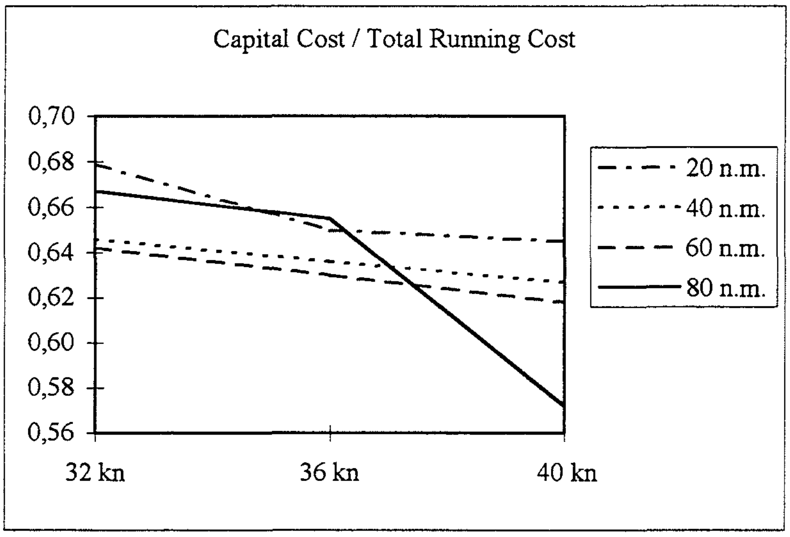


Figure 7.3.3: Effect of Parametric Variations of Crossing Distance

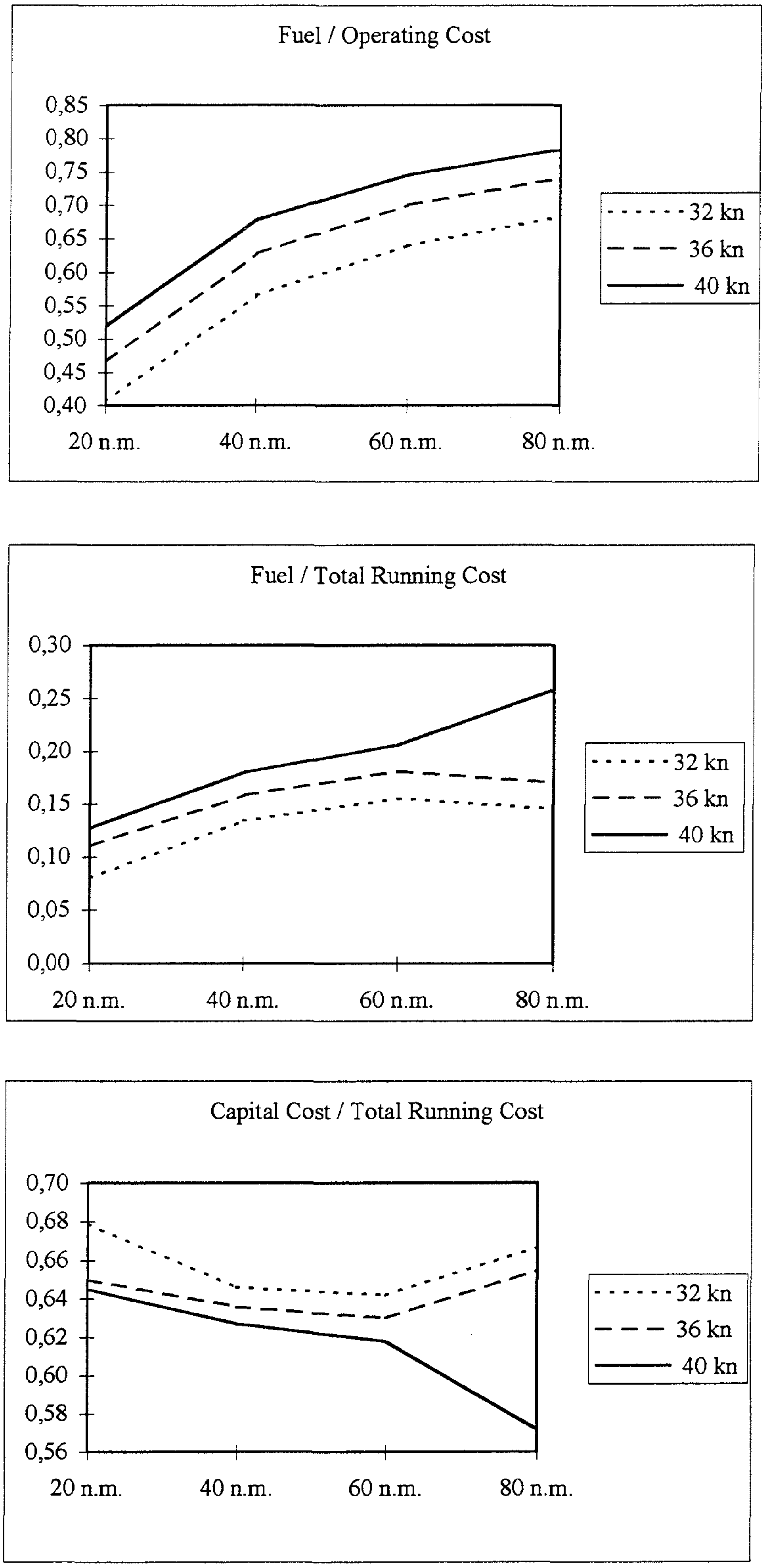


Table 8.1.1: Selected Set of Control Factors

no.	Design Parameter
1	Seating area per passenger, A_S/N_P
2	Total additional areas for use by passengers, A_P/A_S
3	Choice of main engines (diesels, CODAG, gas turbines)
4	Choice of structural material (aluminium, steel, combination)
5	Choice of propulsors (waterjets, different propeller types)
6	Service speed, V_S
7	Passenger capacity, N_P
8	Vehicle capacity, N_V
9	Length-displacement ratio, $L/\nabla^{1/3}$
10	Breadth-draught ratio, B/T
11	Block coefficient, C_B
12	Hull separation-length ratio, S/L (catamarans only)
13	Diesel engine speed, n

Table 8.2.1: Selected Set of Noise Factors

no.	External (Uncontrollable) Parameter
1	Fuel price
2	Significant wave height, $H_{(1/3)}$
3	Wave period, T
4	Required power margin
	Additional operating parameters: Crossing distance, Speed restriction distance, Reduced speed, Operating days per year
	Additional economic parameters: Opportunity interest rate, Economic life, Borrowing and loan repayment parameters

Table 8.4.1: Assumed Operating Pattern

Passenger capacity	620
Vehicle capacity	160
Crossing distance (n.m.)	40
Full service speed (kn)	36
Reduced speed (kn)	12
Speed restriction area (n.m.)	4
Manoeuvring time at each port (min)	10
Turnaround time at each port (min)	30
Total round trip time (h:min)	4:20
Round trips per day	4
Operating days per year	330

Table 8.4.2: Generation of Designs (L18 OA, 8 CFs)

Monohulls								
level	A_S/N_P	A_P/A_S	eng	hull	$L/\nabla^{1/3}$	B/T	C_B	prop
1	0.85	1.15	D	Al	7.2	4.6	0.35	P
2	1.05	1.30	CDG	AlSt	7.7	5.0	0.40	WJ
3	1.25	1.45	GT	St	8.2	5.4	0.45	-
Catamarans								
level	A_S/N_P	A_P/A_S	eng	hull	$L/\nabla^{1/3}$	B_H/T	S/L	prop
1	0.80	1.30	D	Al	8.6	1.6	0.21	P
2	1.10	1.50	CDG	AlSt	9.0	2.0	0.23	WJ
3	1.40	1.70	GT	St	9.4	2.4	0.25	-

Table 8.4.3: Generation of Scenarios (L9 OA, 4 NFs)

level	$H_{(1/3)}$	fuel price	power margin	T (*)		
1	2.1	130	15	5.9	7.1	8.1
2	2.5	150	20	6.2	7.3	8.3
3	2.9	200	25	6.5	7.5	8.5
	m	$/t	%	s		
(*) note that wave period is a sliding noise factor, i.e. its set of three levels is different for each of the three significant wave height levels						

Table 8.4.4: Operating Requirements (Primary Goals)

Attribute	should be:	preferably	definitely	
Building cost	less than	33	40	M$
Annual fuel cost	not much higher than	2.3	-	M$
Passenger area	at least	1000	700	m^2
M.S.I.	less than	10	20	%
Power increase	less than	10	20	%
Availability	at least	95	80	%
Attractiveness	much better than	-	average	*
		fully satisfactory	marginally acceptable	
* assumed attractiveness index: 1-5 scale; 1 = v. low, 3 = average, 5 = v. high				

Table 8.4.5: Membership Functions

Low building cost	$m = 1-\left(\frac{x-a}{b-a}\right)^2$ $33 = a < x < b = 40$	Low annual fuel cost	$m = \frac{\cos\left(\frac{(x-a)\pi}{ka-a}\right)}{2} + 0.5$ $(2.3 * k') = a < x < ka \quad k = 1.4,\ k' = 1.2$
Low M.S.I.	$m = 1-\left(\frac{x-a}{b-a}\right)^2$ $10 = a < x < b = 20$	Large passenger areas	$m = \frac{x-a}{b-a}$ $\quad 700 = a < x < b = 1000$
Low power increase	$m = 1-\left(\frac{x-a}{b-a}\right)^2$ $10 = a < x < b = 20$	High attractiveness	$m = \frac{\sin\left[\left(\frac{(x-a)\pi}{ka-a}\right) - \frac{\pi}{2}\right]}{2} + 0.5$ $(3 * k') = a < x < ka \quad k = 1.25,\ k' = 1.2$
High availability	$m = \frac{x-a}{b-a}$ $\quad 80 = a < x < b = 95$		

Table 8.4.6: Generation of 2nd-Cycle Designs

Monohulls				
level	A_P/N_P	$L/\nabla^{1/3}$	B/T	C_B
1	1.60	7.5	5.1	0.38
2	1.70	7.7	5.3	0.40
3	1.80	7.9	5.5	0.42
Catamarans				
level	A_P/N_P	$L/\nabla^{1/3}$	B_H/T	S/L
1	1.70	9.2	1.5	0.22
2	1.80	9.4	1.7	0.23
3	1.90	9.6	1.9	0.24

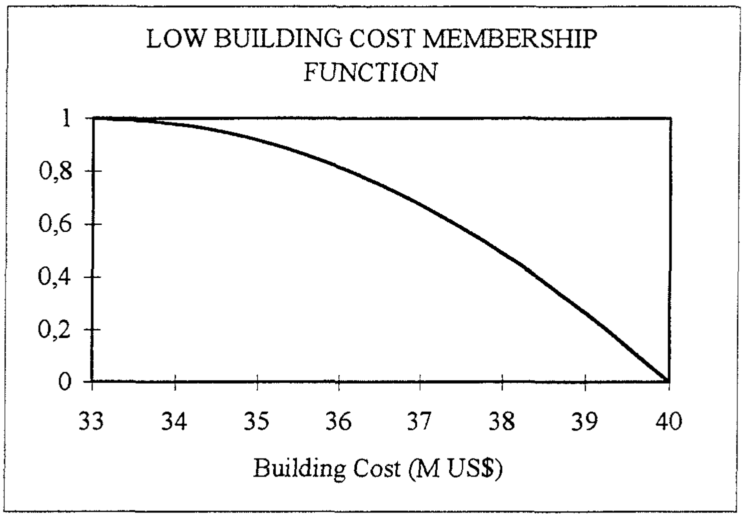
Table 8.4.7: Sensitivity Analysis (Catamarans)

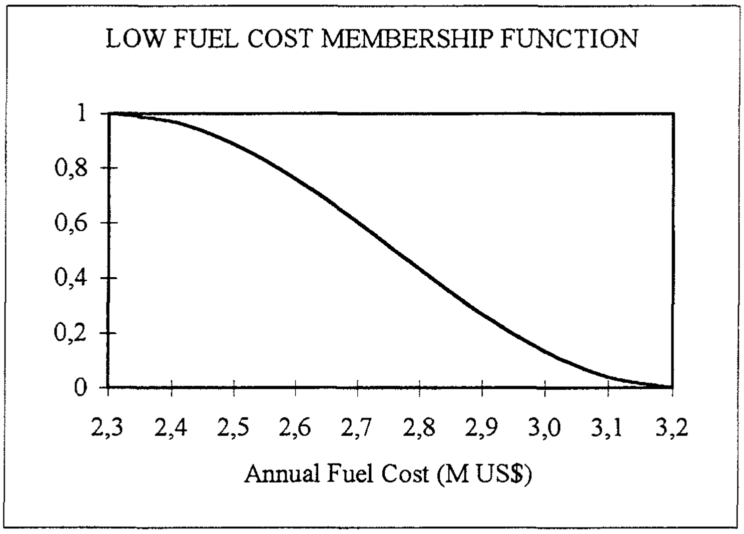
	1	2	3	4	5	6	7	8	9	μ	σ	η
1	.756	.751	.741	.737	.735	.739	.627	.644	.651	.709	.052	-3.054
2	.746	.746	.746	.741	.743	.744	.630	.654	.676	.714	.047	-2.980
3	.812	.805	.766	.755	.756	.752	.688	.676	.693	.745	.049	-2.611
4	.789	.738	.671	.755	.739	.727	.722	.707	.699	.727	.034	-2.789
5	.920	.914	.879	.860	.843	.868	.644	.699	.740	.819	.099	-1.932
6	.899	.902	.896	.894	.898	.901	.847	.855	.869	.885	.022	-1.073
7	.938	.935	.931	.929	.936	.934	.884	.893	.911	.921	.020	-0.718
8	.901	.894	.867	.541	.536	.566	.527	.533	.545	.657	.174	-4.317
9	.861	.852	.727	.828	.740	.844	.582	.706	.750	.766	.091	-2.511

Table 8.4.8: Final Choice: Characteristics of Best Monohull and Best Catamaran

Monohull with highest S/N			
L_{WL} = 92.83m	L_{OA} = 105.83m	B = 16.11m	T = 2.93m
Δ = 1796t			P = 28800kW
eng = diesels	hull = al. alloy	prop = w/jets	η = -1.035
Catamaran with highest S/N			
L_{WL} = 71.62m	L_{OA} = 81.64m	B = 22.60m	T = 2.85m
Δ = 907t	B_H = 5.41m	S = 17.19m	P = 22500kW
eng = diesels	hull = al. alloy	prop = w/jets	η = -0.698

Figure 8.4.1: Membership Functions





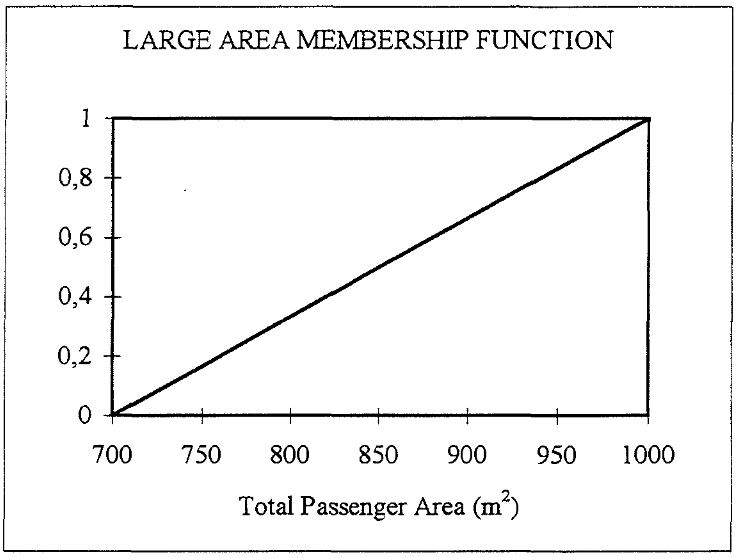
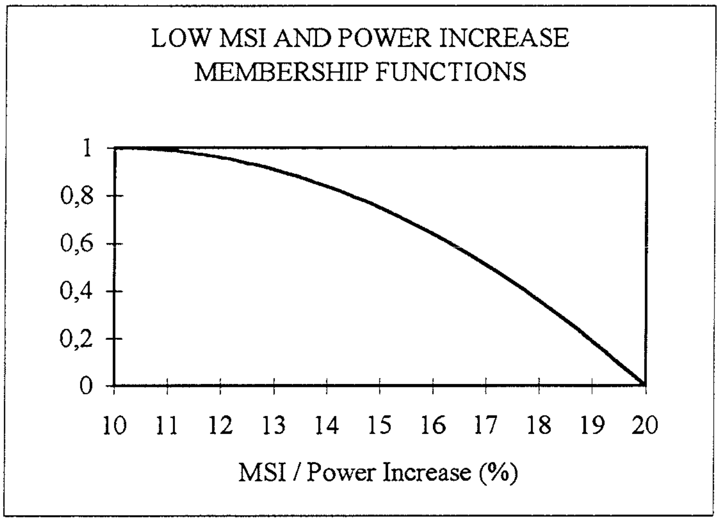
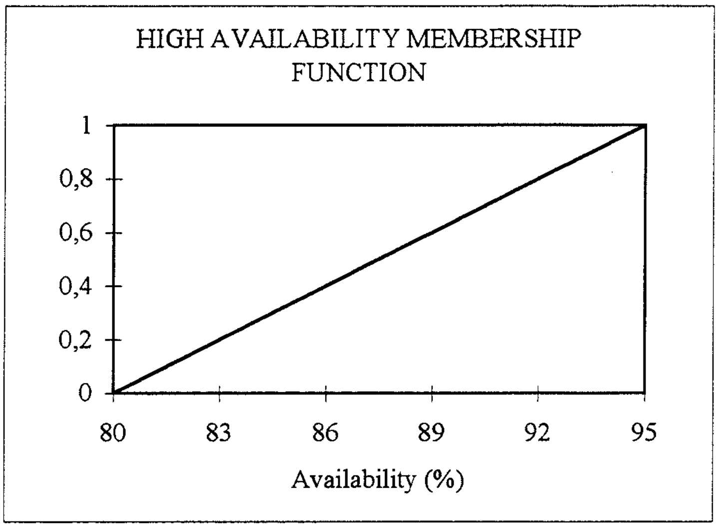
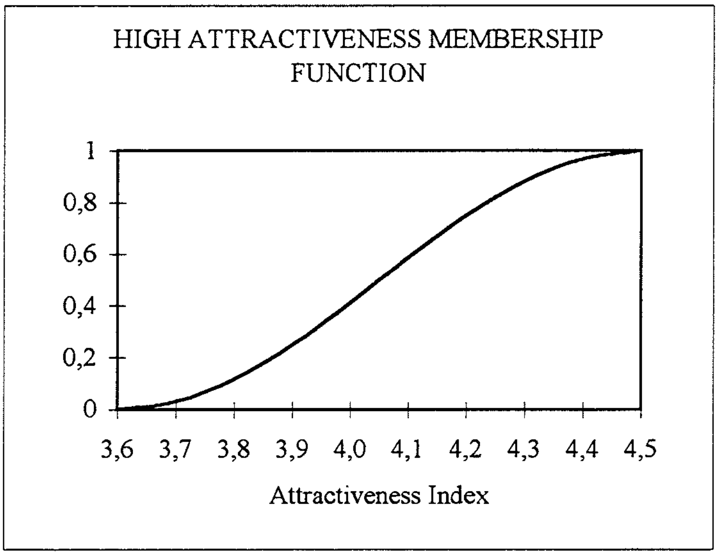


Figure 8.4.1: Membership Functions (cont'd)







APPENDIX A: DATABASE OF HIGH-SPEED FERRIES

The assembled database of high-speed ferries is presented in this appendix. The database has been developed in order to assist the generation of feasible and realistic technical designs. Its role is therefore dual: to provide data to be analysed statistically allowing the derivation of regression formulae and ratios to be used for calculations of main dimensions; and to provide a checking facility allowing the validation of generated designs by comparison with existing designs. The focus during the development of the database has therefore been on technical aspects such as dimensions, areas, capacities and machinery installations, as well as some operational and configurational aspects.

All the high-speed ferries that could be found have been included in the database. Due to the thoroughness of the investigation it is believed that the vast majority of operating fast ferries of current technology have been included. Apart from existing vessels, proposed new designs have also been included in the cases where they represent fully developed detailed designs and the available technical information is adequate.

The result was a large database which includes hundreds of different vessels of numerous hull forms and variants, see Table 5.2.1. Vessel types such as hydrofoils and hovercraft which are considered of reduced interest today for ferry applications have not been included. The database includes monohulls, catamarans, SWATHs, SESs, wave piercers and foil-assisted catamarans. However the number of vessels for many hull types is too small to allow satisfactory statistical analyses to be performed and for this reason a full analysis has been performed only for monohulls and conventional catamarans; these two vessel types do however represent the majority of operating fast ferries, as can be seen in the database itself.

In the databases each row represents one vessel and the data are in columns. Variants of the same design found often with slightly different characteristics from one operator to another are logged separately and are generally treated as different vessels. The amount of data included is very large and the databases have close to 50 columns each. An outline description of their structure is given here indicating how they are used. There are four databases representing the four major vessel categories, namely passenger-only monohulls (PM), passenger-only multihulls, vehicle/passenger monohulls (VM) and vehicle/passenger multihulls.

The two multihull databases include all the different hull forms but the analysis has been performed only for catamarans (PC and VC) as has been discussed earlier.

The table that follows provides a summary listing of the contents of the databases. The first two columns include the vessel's code and the designer and constructor/ shipyard. Then the main dimensions are given. Overall length is available for all vessels while length between perpendiculars is available for a few vessels only. Waterline length is available for many vessels and for those for which it is not it is calculated as is described in Chapter 5. Breadth, depth and draught follow; the first two are accompanied by an indication of whether they are moulded or overall when this is known and draught by an indication of whether it includes ride control foils or not. For catamarans hull separation is also included, which is measured on general arrangement plans as it is never included in the technical specifications of the vessels. These are the main input dimensions to be analysed in order to allow the development of the algorithm for calculations of main dimensions.

Vessel capacities and size parameters follow. Deadweight, displacement and tonnage (GRT) are included for the few vessels for which they are available. The following columns include passenger and vehicle, where applicable, capacities. Vehicle capacities represent passenger cars but additional information concerning alternative loading options including buses and/or trucks are also logged.

Service and maximum speeds are then given followed by a column which includes information on the main machinery installation. This includes the type and number of main engines and their installed power. The following three columns include the range and fuel and water capacities. These are secondary data which are included because they may be useful for some investigations.

The next three columns include importance reference information. The first indicates whether a general arrangement plan is available for each vessel (yes/no) with a separate indication of vessels for which full general arrangement plans are not available but profile plans or other partial information is; these are not fully useful for area calculations but may be useful in other contexts. The following column indicates whether a detailed deadweight analysis is available for the vessel, which is useful for the development and validation of the algorithm for mass estimates, see Chapter 5. Then the source of the information is indicated, i.e. the journal and issue where the vessel was found or in a small number of cases another source such as a commercial brochure or a paper.

The input part of the databases concludes with two columns including one with additional capacities and weights, such as lubricants, diesel oil, sewage and sludge, and one for any additional information; the latter mainly includes catamaran demihull beam, measured on general arrangement plans as it is not included in technical specification either, and in some cases other data such as endurance, cargo capacity or vehicle lane capacity (total lane length). There is also a column which includes details about passenger distribution which can be useful for the investigation of alternative deck configurations.

The remaining columns are output columns including the results of calculations performed using the input data in the databases. Froude numbers based on waterline length and service and maximum speeds are the first data in this part. Length-beam ratios follow for both overall and waterline lengths, followed by hull separation-length ratios for catamarans.

Major area parameters and ratios are then calculated; these are used for the generation of the data plots in Chapter 5 which in turn allow the development of the algorithm for the calculation of main dimensions. These columns include seating areas, seating area per passenger ratios, total passenger areas and the relevant ratios per passenger, total passenger area - seating area ratios and, where applicable, vehicle areas and area per vehicle ratios.

Additional hull ratios are included in the last few columns: breadth-draught ratio, demihull beam-draught ratio and waterline length-demihull beam ratio for catamarans, length-displacement ratio for the few vessels with known displacement, and finally the length-beam product which is of great importance for the dimensions algorithm.

Field Vessel category:	PM	PC	VM	VC
Ship code	*	*	*	*
Designer / Constructor	*	*	*	*
Overall length, L_{OA} (m)	*	*	*	*
Length between perpendiculars, L_{BP} (m)	*	*	*	*
Waterline length, L_{WL} (m)	*	*	*	*
Beam, B (m)	*	*	*	*
(overall/moulded)	*	*	*	*
Depth, D (m)	*	*	*	*
(overall/moulded)	*	*	*	*
Draught, T (m)	*	*	*	*
Hull separation, S (m)		*		*
Deadweight, DWT (t)	*	*	*	*
Displacement, Δ (t)	*	*	*	*
Gross register tonnage, GRT	*	*	*	*
Passenger capacity, N_P	*	*	*	*
Vehicle capacity, N_V			*	*
Service speed, V_S (kn)	*	*	*	*
Maximum speed, V_M (kn)	*	*	*	*
Propulsion plant, configuration and installed power (kW)	*	*	*	*
Range, R (n.m.)	*	*	*	*
Fuel capacity (l)	*	*	*	*
Fresh water capacity (l)	*	*	*	*
General arrangement plan (y/n)	*	*	*	*
Deadweight analysis (y/n)	*	*	*	*
Data source	*	*	*	*
Other capacities and weights	*	*	*	*
Other	*	*	*	*
Froude number based on L_{WL} and V_S, $Fn_{S/WL}$	*	*	*	*
Froude number based on L_{WL} and V_M, $Fn_{M/WL}$	*	*	*	*
Overall length - beam ratio, L_{OA}/B	*	*	*	*
Waterline length - beam ratio, L_{WL}/B	*	*	*	*
Separation - waterline length ratio, S/L_{WL}		*		*
Seating area, A_S (m^2)	*	*	*	*
Seating area per passenger, A_S/N_P (m^2)	*	*	*	*
Total passenger area, A_P (m^2)	*	*	*	*
Total area per passenger, A_P/N_P (m^2)	*	*	*	*
Total passenger area - seating area ratio, A_P/A_S	*	*	*	*
Vehicle area, A_V (m^2)			*	*
Area per vehicle, A_V/N_V (m^2)			*	*
Beam - draught ratio, B/T	*	*	*	*
Waterline length - beam product, $L_{WL} \times B$ (m^2)	*	*	*	*
Passenger distribution	*	*	*	*
Demihull beam - draught ratio, B_H/T		*		*
Waterline length - demihull beam ratio, L_{WL}/B_H		*		*
Waterline length - displacement ratio, $L_{WL}/\nabla^{1/3}$	*	*	*	*

Ship Code	Des./Cons.	L_{OA} (m)	L_{BP} (m)	L_{WL} (m)	B (m)		D (m)		T (m)	S (m)	DWT (t)	Δ (t)	GRT	Pax	V_S (kn)	V_M (kn)
PC1a	Rosendal Werft	29.00	27.40	27.20	8.00		3.10		1.50	5.50				100	32.0	
PC1b	Rosendal Werft	29.00	26.10	27.20	8.10		3.10		1.50	5.55				100	32.0	
PC2a	Rosendal Werft	36.00	32.70	31.60	9.60		3.70		1.70	6.20				308	35.0	
PC2b	Rosendal Werft	36.00	32.77	31.60	9.90				1.74	6.45	PL 33.5			312	35.0	
PC3	Incat / Nichols	32.40		*28.70*	9.10	oa			1.40					49	25.0	
PC4a	Austal	40.10		35.00	11.50	mld			1.40					355	40.5	
PC4b	Austal	40.10		35.00	11.50	mld			1.40					338	33.5	
PC4c	Austal	40.10		35.00	11.50	mld			1.40					332	40.2	
PC5	Lock Crowther	35.00		32.15	11.60				1.60	8.60				310	29.0	30.0
PC6a	Marinteknik	42.10		36.80	11.00	mld			1.20	6.95				395	40.0	42.0
PC6b	Marinteknik	42.00		37.95	11.50	mld	3.70	mld	1.30	7.65	47			506	33.0	
PC6c	Marinteknik	42.10		36.00	11.00	mld				7.05				381	50.0	
PC7	Austal	43.40		37.70	11.20	mld	3.90	mld	1.30	7.45			543	331	42.5	
PC8a	Båtservice	38.00		33.95	11.20		3.90		1.60					336	35.0	
PC9	Incat Designs	47.40		46.40	12.20	oa			1.60	9.00				550		
PC10a	Kvaerner Fjellstrand	40.00		35.55	10.10		3.97	mld	1.50					306	37.5	
PC10b	Kvaerner Fjellstrand	40.00		35.55	10.10		3.97	mld	1.50					333	37.5	
PC10c	Kvaerner Fjellstrand	40.00		35.55	10.10		3.97	mld	1.50					420	37.5	
PC11	Oceanfast	35.60		29.10	10.60		3.70	mld	1.40					250	35.0	37.0
PC12a	Oceanfast	40.00		33.20	12.00		3.70	mld	1.40					366	31.0	33.0
PC12b	Oceanfast	40.00		33.20	12.00		3.70	mld	1.40					300	34.0	36.0
PC13a	Oceanfast	42.00		35.20	12.00		3.70	mld	1.50					380	42.0	44.0
PC13b	Oceanfast	42.00		35.70	12.00		3.70	mld	2.20					415	41.0	43.0
PC13c	Oceanfast	42.00		35.70	12.00		3.70	mld	2.20					532	38.0	40.0
PC14	Oceanfast	55.00		48.30	15.00		3.70	mld	1.50					572	38.0	40.0
PC15	Marinette Marine	30.00		27.00	9.10				0.90					400	35.0	38.0
PC16a	FBM	45.00		43.00	11.80	oa			1.40	8.60				496	20.0	
PC16b	FBM	45.00		43.00	11.80	oa			1.38	8.60				496	23.0	25.0
PC17	Nigel Gee Associates	40.10		33.00	10.60	mld			1.60					350	35.0	
PC18	WaveMaster	42.00		36.00	12.00	mld	3.70	mld	1.50/2.50	8.30				380	42.0	
PC19	Incat Designs	49.92		49.68	12.40				1.80	9.40				550	40+	
PC20	Aluminium Craft	38.00		34.45	12.00		4.45			8.30			567	360	32.0	34.0
PC21	Lloyd's Ships	38.00		*33.66*	12.20				1.80		40	161		400	30.0	
PC22a	Advanced Multihull Designs	41.27		36.23	12.00				1.50					301	32.0	
PC23a	Iris	39.92		38.00	10.24	oa			1.50		35			160	26.6	32.0
PC23b	Iris	39.92		38.00	12.74	oa			1.56		51			240	29.8	33.3
PC23c	Iris	39.92		38.00	12.74	oa			1.62		72			384	31.6	36.1
PC24	Famille Dufour	38.60		34.20	10.40				1.40			122		300	30.0	

L PC - 1a

Propulsion Plant / kW	Range (n.m.)	Fuel (lt)	Fresh Water (lt)	G.A.	DWT	Source	Other Capacities / Weights	Other	$Fn_{S/WL}$	$Fn_{M/WL}$	L_{OA} / B
D 2 x 1040				*		FF / I-II '95		cargo 7	1.008		3.63
D 4 x 550				*		FF / VII-VIII '95		cargo 7	1.008		3.58
D 4 x 735				*		FF / I-II '95			1.023		3.75
D 4 x 735		6500	1500	*		FF / VII-VIII '95	sew 1500		1.023		3.64
D 2 x 772		2 x 8525	3 x 2460			FF / I-II '95	sew 3140 / store 1.13		0.767		3.56
G 2 x 2600		17000	1500			FF / I-II '95			1.125		3.49
D 2 x 2000		10000	1500			FF / X '95			0.930		3.49
G 2 x 2600		20000	1500			FF / X '95			1.116		3.49
D 2 x 1440				*		FF / III '95			0.840		3.02
D 4 x 1415	275			*		FF / IV '95		B_H 3.55	1.083	1.137	3.83
D 2 x 1935	300	2 x 5000	1 x 1000	*		FF / IV '95		B_H 3.35	0.880		3.65
D 4				*		SB / I-II '95		B_H 3.70	1.369		3.83
D 4 x 1960		14000	1500	*		FF / V '95		B_H 3.90	1.137		3.88
D 4 x 735		8000	1000	*		FF / VI '95	sew 800		0.987		3.39
D 2 x 2000				*		FF / VI '95		B_H 3.20			3.89
D 2 x 2000		2 x 6000	1 x 1500	*		FF / VII-VIII '95	bilge 1 x 1500 / sew 1 x 1500		1.033		3.96
D 2 x 2000		2 x 6000	1 x 1500	*		FF / I-II '96	bilge 1 x 1500 / sew 1 x 1500		1.033		3.96
D 2 x 2000		2 x 6000	1 x 1500	*		FF / I-II '96	bilge 1 x 1500 / sew 1 x 1500		1.033		3.96
D 2	200	10000	1000			FF / VII-VIII '95			1.066	1.127	3.36
D 2	250	12000	1500			FF / VII-VIII '95			0.884	0.941	3.33
D 2						FF / VII-VIII '95			0.969	1.026	3.33
D 2		14000	1500			FF / VII-VIII '95			1.163	1.218	3.50
D 2						FF / VII-VIII '95			1.127	1.182	3.50
D 2	225	30000	2000			FF / VII-VIII '95			1.045	1.100	3.50
D 4	390	22000	1500			FF / VII-VIII '95			0.898	0.945	3.67
G 2 x 1125		2 x 3800		*		FF / IX '95			1.106	1.201	3.30
D 2 x 948	1000+	23000	1000	*		FF / X '95	LO 100		0.501		3.81
D 2 x 960	184			*		SB / XI '95			0.576	0.626	3.81
D 2 x 2000	400	12000		*		FF / X '95		E 6	1.001		3.78
D 4 x 1941	340	19000 / 39000	2000	*		FF / XII '95	sullage 1000	B_H 2.75	1.150		3.50
D 4 x 1932				*		FF / XII '95		B_H 3.00	0.932		4.03
D 2 x 1940	400	12000	1800			FF / I-II '96		B_H 3.20	0.896	0.952	3.17
D 2 x 2000		10500	4000	*		FF / I-II '96	FO 11.5 / FW 3.8	B_H 3.00	0.849		3.11
D 2 x 2000						FF / I-II '96			0.873		3.44
D 2 x 960			760			FF / I-II '96	FO 4.2	E 10	0.709	0.853	3.90
D 2 x 1524			1100			FF / I-II '96	FO 6.6	E 10	0.794	0.887	3.13
D 2 x 2032			1800			FF / I-II '96	FO 8.8	E 10	0.842	0.962	3.13
D 2 x 1618						FF / I-II '96			0.843		3.71

2 PC-1b

L_{WL} / B	S / L_{WL}	A_S (m^2)	A_S/p (m^2)	A_P (m^2)	A_P/p (m^2)	A_P / A_S	B/T	$L_{WL} * B$	pax distribution	B_H / T	L_{WL} / B_H		$L_{WL}/\nabla^{1/3}$	∇	$L_{WL}/\nabla^{1/3}$
3.40	0.20	78	0.78	97	0.97	1.24	5.33	217.6							
3.36	0.20	81	0.81	104	1.04	1.28	5.40	220.3							
3.29	0.20	271	0.88	333	1.08	1.23	5.65	303.4							
3.19	0.20	271	0.87	333	1.07	1.23	5.69	312.8							
3.15							6.50	261.2							
3.04							8.21	402.5	266 + 81 up + 8 VIP						
3.04							8.21	402.5	262 + 60 up + 16 VIP						
3.04							8.21	402.5	256 + 64 up + 12 VIP						
2.77	0.27	221	0.71	256	0.83	1.16	7.25	372.9							
3.35	0.19	263	0.67	311	0.79	1.18	9.17	404.8		2.96	10.37	3.55		125.4	9.26
3.30	0.20	395	0.78	412	0.81	1.04	8.85	436.4		2.58	11.33	3.35		132.2	9.39
3.27	0.20	263	0.69	311	0.82	1.18		396.0			9.73	3.70			
3.37	0.20	266	0.80	321	0.97	1.21	8.62	422.2		3.00	9.67	3.90		152.9	8.88
3.03		249	0.74	287	0.85	1.15	7.00	380.2							
3.80	0.19	367	0.67	455	0.83	1.24	7.63	566.1		2.00	14.50	3.20		190.1	10.17
3.52		179	0.58	210	0.69	1.17	6.73	359.1							
3.52		200	0.60	227	0.68	1.14	6.73	359.1							
3.52		247	0.59	291	0.69	1.18	6.73	359.1							
2.75							7.57	308.5	222 + 28 up						
2.77							8.57	398.4	282 + 84 up						
2.77							8.57	398.4	252 + 48 up						
2.93		274	0.72	320	0.84	1.17	8.00	422.4	274 + 106 up						
2.98							5.45	428.4	334 + 81 up						
2.98							5.45	428.4	406 + 126 up						
3.22							10.00	724.5	418 (+30 VIP) + 124 up						
2.97		307	0.77	319	0.80	1.04	10.11	245.7							
3.64	0.20	275	0.55	314	0.63	1.14	8.43	507.4							
3.64	0.20	275	0.55	314	0.63	1.14	8.55	507.4							
3.11		232	0.66	255	0.73	1.10	6.63	349.8							
3.00	0.23	249	0.66	290	0.76	1.16	8.00	432.0		1.83	13.09	2.75		118.8	9.23
4.01	0.19	370	0.67	447	0.81	1.21	6.89	616.0		1.67	16.56	3.00		214.6	10.45
2.87	0.24	296	0.82	330	0.92	1.11		413.4			10.77	3.20			
2.76							6.78	410.7		1.67	11.22	3.00	7.86	145.4	8.06
3.02		355	1.18	386	1.28	1.09	8.00	434.8							
3.71							6.83	389.1							
2.98							8.17	484.1							
2.98							7.86	484.1							
3.29							7.43	355.7					8.76		

3 PC-1c

		LOA														
PC25	SBF	31.70		*28.08*	9.60				1.00					250	32.0	35.0
PC26a	Westamarin	42.00		37.37	10.00	mld			1.75/2.50					400	38.0	42.0
PC26b	Westamarin	42.00		37.37	10.00	mld			1.80/2.55	6.85			499	400	38.0	42.0
PC27	Ulstein	38.00		30.55	10.00				1.00	6.05				225		
PC28	Oceanfast	44.80		38.30	12.00	oa	3.70	mld	2.20					450	43.0	46.0
PC29	Daewoo	40.25		*35.65*	9.30	mld			1.50					350	38.0	40.0
PC30a	Semo	40.00	36.50	*36.50*	11.50		3.95		1.50/			155		351	35.0	
PC31a	FBM	45.00		40.00	11.80		4.76		1.45	8.50	PL 36	188		312	44.0	
PC31b	FBM	45.00		40.00	11.80		4.76		1.37	8.50		188		332	45.0	
									ride control							
		1.13														
PF1a	Hyundai	45.50		*37.98*	11.40	oa	5.10		1.60					300	35.0	
PF1b	Hyundai	45.00		*37.56*	11.40	oa	5.10		1.60					300	40.0	
PF2a	Marinteknik	45.00	37.00	*37.00*	11.00	mld	4.10	mld	1.40/2.40					400	50.0	54.0
PF2b	Marinteknik	45.00	37.00	*37.00*	11.00	mld	4.10	mld	1.30/2.40	7.25	180			445	41.5	
PF3a	Kvaerner Fjellstrand	35.00		29.65	12.00		4.20	mld	2.55/4.70				450	407	45.0	
PF3b	Kvaerner Fjellstrand	35.00		29.65	12.00		4.20	mld			50			403		
									foils							
		1.20														
PS1a	International Shipyards / Ulstein	39.60		33.30	11.90		4.00	mld	1.00/2.60		waterjets			350	45.0	48.0
PS1b	International Shipyards / Ulstein	38.30		33.30	11.90		4.00	mld	2.40/3.60		z-pod			350	45.0	48.0
PS2	Semo	40.00		35.20	11.60				0.60/1.90					400		50.0
PS3	Samsung	36.70		32.25	12.00	oa	4.00		0.80/2.00			160		352	45.0	
PS4	International Shipyards	38.70		*33.19*	11.60				2.24/3.44					350	45.0	48.0
PS5	Oceanfast / Ulstein	35.60		29.30	10.60		3.70	mld						250	35.0	37.0
PS6	Oceanfast / Ulstein	39.60		33.30	11.90		3.70	mld						350	31.0	33.0
PS7	Oceanfast / Ulstein	42.00		35.80	11.90		3.90	mld						380	42.0	44.0
PS8	Oceanfast / Ulstein	55.00		48.15	15.00		4.30	mld						548	38.0	40.0
									cushion							
		1.17														
PW1	NQEA	45.45		39.56	16.24				1.90	13.15	53			450		36.0
PW2	Advanced Multihull Designs	42.50		36.95	12.20	oa			1.40/2.50	8.95	38			350	33.0	36.0
									ride control							

4 PC-2a

D 2 x 1435						SB / V '94			0.992	1.085	3.30
D 4 x 1485						FF / III '95			1.021	1.129	4.20
D 4 x 1485		2 x 3200 + 2 x 420(	2 x 1000	*		FF / VII-VIII '95	LO 1 x 250 / sew 1 x 2000	B_H 2.75	1.021	1.129	4.20
				*		SB / VI-VIII '94		B_H 3.60			3.80
D 4 x 2000						FF / XII '95		B_H 3.15	1.141	1.221	3.73
D 2 x 2000	200	14000	1500	*		SB / I-II '95			1.045	1.100	4.33
D 2 x 1940				*		FF / IV '95			0.952		3.48
G 2 x 4200				*		SB / I-II '95			1.143		3.81
G 2				*		SB / XI '93					3.81
											3.63
D 2 x 4105	500					SB / XI '95			0.933		3.99
D 2 x 4105						SB / I-II '95			1.072		3.95
D 4	200					FF / IV '95			1.350	1.458	4.09
D 4 x 1470		2 x 7000	1 x 2500	*		FF / I-II '96		B_H 3.75	1.121		4.09
G 2 x 4474	300	2 x 10000	1 x 250	*		FF / VII-VIII '95	LO 1 x 400 / bilge 1 x 1000 / sew 1 x 1500		1.358		2.92
				*		SB / V '94					2.92
D	400 / 300	14000	1500	*		FF / III '95			1.281	1.366	3.33
D	400 / 300	14000	1500	*		FF / III '95			1.281	1.366	3.22
D 2 x 1970				*		SB / I-II '95				1.384	3.45
D 2 x 2000	250			*		FF / V '95			1.302		3.06
D 2						SB / I-II '95			1.283	1.369	3.34
D 2	200	10000	1000			FF / III '95			1.062	1.123	3.36
D 2	250	12000	1500			FF / III '95			0.882	0.939	3.33
D 4	185	14000	1500			FF / III '95			1.153	1.208	3.53
D 4	390	22000	1500			FF / III '95			0.900	0.947	3.67
D 4 x 1343	220	2 x 6000 / 2 x 3600(	2 x 3000	*		FF / VII-VIII '95	sullage 1 x 4500	B_H 3.00		0.940	2.80
D 2 x 1960		14000	1000	*		FF / XII '95			0.892	0.973	3.48

LWL/B	S/LWL	As(m²)	As/T(m²)	[illegible]	Ap/T(m²)	Ap/As	B/T	LWL·B	pax distribution	φH/T	LWL/βH		LWL/V	V	LWL/V
2.93							9.60	269.6	218 + 32 up (1st calss)						
3.74							5.71	373.7	314 + 86 up						
3.74	0.18	275	0.69	334	0.84	1.21	5.56	373.7		1.53	13.59	2.75		148.0	8.90
3.06	0.20	180	0.80	223	0.99	1.24	10.00	305.5		3.60	8.49	3.60		88.0	8.65
3.19		297	0.66	389	0.86	1.31	5.45	459.6	342 + 108 up	1.43	12.16	3.15		212.3	8.09
3.83							6.20	331.5							
3.17		237	0.68	291	0.83	1.23	7.67	419.8					8.63		
3.39	0.21	264	0.85	298	0.96	1.13	8.14	472.0							
3.39	0.21	256	0.77	322	0.97	1.26	8.61	472.0							
3.23	0.21		0.73		0.86	1.18	7.47			2.23	11.79				
3.33							7.13	433.0	208 + 92 up						
3.29							7.13	428.2	208 + 92 up						
3.36							7.86 / 4.58	407.0							
3.36	0.20	317	0.71	388	0.87	1.22	8.46 / 4.58	407.0		2.88	9.87	3.75			
2.47		304	0.75	352	0.86	1.16	4.71 / 2.55	355.8							
2.47		304	0.75	352	0.87	1.16		355.8							
2.80		217	0.62	263	0.75	1.21	11.90 / 4.58	396.3							
2.80		217	0.62	263	0.75	1.21	4.96 / 3.31	396.3							
3.03		258	0.65	335	0.84	1.30	19.33 / 6.11	408.3							
2.69		294	0.84	373	1.06	1.27	15.00 / 6.00	387.0					7.55		
2.86							5.18 / 3.37	385.0							
2.76								310.6							
2.80								396.3							
3.01								426.0							
3.21								722.3							
2.44	0.33	380	0.84	480	1.07	1.26	8.55	642.5							
3.03	0.24	280	0.80	299	0.85	1.07	8.71	450.8							

6 PC-2c

Ship Code	Designer / Constructor	LOA (m)	LPP (m)	LWL (m)	B (m)		D(m)		T(m)	S(m)	DWT(t)	Δ(t)	GRT	Pax	Vs (kn)	Vm (kn)
		1.15														
PSW1	Almaz/Agat/Sukhoi	32.30			10.50	oa			2.30		275			186	28.0	
PF4	Almaz/Agat/Sukhoi	44.90			11.70				1.20/2.30					350	46.0	
PC32	Sabre	32.00			9.30				1.70					300		28.0
PC33	Incat Designs	33.98			9.45		2.74		1.22					365	31.5	
PC34	Marinteknik	32.80							1.20/2.50		21			200		50.0
PC35	FBM	50.00		45.11	11.80				1.34					403	36.0	
PSW2	FBM	39.70			14.20				2.00					400	29.0	30.0
PC30b	Semo	40.00	36.50		10.40	oa	4.10		1.35				290	372	34.0	39.5
PSW3	SWATH Int'l / Nichols	37.52		32.40	18.07	oa			3.44		64		1025	367	27.0	
PC36	Advanced Multihull Designs	42.50			11.20									344	32.0	
PC37	FBM	31.50		27.50	8.40				1.10					120		38.0
PC38	FBM	39.20		35.30	10.00				1.35					306		38.0
PC22b	A.M.D. / Dakota Creek	41.27			11.50	oa			1.50		40			325	32.0	36.0
PSW4	SWATH International	33.60			16.20	oa			2.90					449	26-34	
PSW5	SWATH International	37.20			18.00	oa			3.50					550	26-34	
PC39	WaveMaster	41.00		37.00	12.00		3.70		2.20					639	26.0	29.0
PC40	Kvaerner Fjellstrand	34.00			10.10				1.50				400	250		32.0
PC19b	Incat / South Australian Ships	49.92		46.68	12.40		4.13	mld	1.80/2.36		48			430		41.0
PC41	New Tech	42.00		36.00	12.00	mld	3.70	mld	1.50			128		380		44.0
PC30c	Semo	40.00	36.50		10.40	oa	4.10		1.35				290	379	34.0	39.0
PSW6	Samsung	34.00			13.00	oa			2.70		41	200		350	30.0	31.5
PC42	Kvaerner Fjellstrand	46.00			12.00	oa					57			440		38.0
PC43	Kvaerner Fjellstrand	35.00			10.10	oa			1.60		32		395	350		32.0
PC44a	Derecktor / NGA	32.00			8.50				1.50					220-300	28.0	
PC44b	Derecktor / NGA	32.00			8.50				1.50					220-300	38.0	
PC45	Derecktor / NGA	36.70			10.00				1.80					400	32.0	
PC46	Derecktor / NGA	37.70		32.90	10.00	mld			1.80		39	143		345	35.0	36.5
PC22c	AMD	41.27		36.23	11.50	mld			1.50		40			301		32.0
PC47	Buro J. de Haas	32.20		30.00	9.50	mld	2.75		1.00					150	27.0	
PC48	WaveMaster	49.00		42.70	12.00				1.60		60			372		40.0
PC49	Austal	30.00		26.25	8.70		3.26	mld	1.11		16	65		140	32.0	
PC4d	Austal	40.10		35.00	11.50	mld	3.80	mld	1.35					318	34.0	
PC4e	Austal	40.10		35.00	11.50	mld	3.80	mld	1.35					338	34.0	
PC50	Austal	44.00			11.80	mld			2.50					500	28.0	
PC51	FBM	46.25		44.25	11.80	oa			1.35					496	25.0	28.0
PC52a	FBM	32.90			8.40				1.25					190	33.0	
PC52b	FBM	32.90		29.50	8.32	oa	3.00		1.25				213	190-3C	34.0	37.0

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PC-3a

Propulsion Plant / kW	Range (n.m.)	Fuel (lt)	Fresh Water (lt)	G.A.	DWT	Source 8	Other capacities / Weights	Other	$Fn_{s/wl}$	$Fn_{m/wl}$	Loa/B
D 2 x 1500	250	9700	2000	*		FF / III,IV '96					
D 2 x 2945	400	12400	2300	*		FF / III,IV '96					
D 2 x 1260		20000	2000			FF / VI '96					
D 4 x 600		10600	950			BWPV `97	sew 760				
D 4 x 735				*		FF / XII `96					
				*		FF / XII `96					
D 2 x 2000				*		SB / V `95		E10			
D 2 x 1100	230	2 x 4000	2000			BWPV `97					
G 2 x 2870	200	14000		*		FAST '95					
D 2 x 2000						SB / I-II '97					
D 2 x 1360				*		F					
D 2						F					
D 2 x 1960		14000	3800	*		F					
				*		F					
				*		F					
D 2 x 2032	400	16000	2000	*		FF / I-II '97	sew 1500 / sul 1000				
D 2 x 1415		2 x 4000	1000	*		FF / I-II '97	sew 1000				
D 4 x 1940	280	19800	2800	*	*	FF / III '97	sew 1000	B_{II} 3.00			
D 4 x 1960	185	12000	1250	*		FF / IV '97					
D 2 x 2000		2 x 4000	2000	*		FF / IV '97					
D 2 x 2000	200				**	F97					
D 4 x 1740		2 x 10000	1 x 1500	*		FF / V '97	sew 1 x 1500 / slu 500				
D 4 x 610		2 x 3000	1 x 800	*		FF / V '97	sew 1 x 1000 / slu 1000				
D 2 x 610						FF / V '97					
D 4 x 610						FF / V '97					
D 4 x 610						FF / V '97					
D 2 x 2000	400	12000		*		FF / V '97					
D 2 x 1960		14000	3800	*		FF / V '97		B_{II} 3.00			
D 2				*		FF / VII-VIII '97	20 bicycles				
D 4 x 1939		40000	3000	*		FF / IX '97					
D 2 x 1499		2 x 3000	1 x 400	*		FF / IX '97	sul 1 x 400				
D 2 x 1980		2 x 5000	1 x 1500	*		FF / IX '97					
D 2 x 1980		2 x 5000	1 x 1500	*		FF / IX '97					
D 2 x 2000						FF / X '97					
D 2 x 1210	1250	23000	1000	*		FF / X '97	LO 100				
D 2 x 1500						FF / XI '97					
D 2 x 1500	120	2 x 1250	1 x 100	*		FF / Oct'98	LO 2 x 100				

PC-3b

230 + 70 up

307 + 96 up

244 + 128 up

in 264 + 148 up / out 20 + 64 + 143

315 + 33 up + 16 VIP + 16 off.

278 + 162 up

270 + 80 up

267 + 78 up

182 + (94+25) up

133 + 7 up

198 + 108 up + 12 VIP

222 + 90 up + 26 VIP

272 + (50+84) up + 94 top

338 + 158 up

pax distribution

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PC-3C

Ship Code	Designer / Constructor	Loa (m)	Lpp (m)	Lwl (m)	B (m)		D (m)		T (m)		DWT (t)	A (t)	GRT	pax	Vs (kn)	VM (kn)
PF5a	Hitachi	39.00			11.40	mld		w/o	1.90			300		200		45.0
PC53	Båtservice	37.15	33.00		10.87	oa	3.90		1.70					199	32.0	
PC26c	Båtservice / Westamarin	42.00		37.40	10.00	mld	4.10	mld	1.80/2.60					392	39.0	
PC8b	Båtservice	38.00			11.46	oa	3.90	mld	1.65					354	35.0	
PC54	Austal	42.10		37.00	11.50	mld	3.70	mld	1.35					352	34.0	
PC55	Incat Designs / Gladding Hearn	33.33		28.96	9.22				1.25					147		34.0
PC56a	Incat Designs / Gladding Hearn	37.07		33.96	9.95				1.60					350		33.0
PC56b	Incat Designs / Gladding Hearn	37.12		33.96	9.95				1.77					350	34.0	38.0
PC57	Dereckter / NGA	45.60		40.15	11.80	mld			1.50			202		304	50.0	52.0
PC58	Austal	48.00			13.00	mld			1.40					516	41.0	
PC59a	Iris	42.77		39.75	13.05	oa			1.80		51			240	29.0	
PC59b	Iris	42.77		39.75	13.30	oa			2.00		72			398	30.0	
PC60	Lindstøl	33.30			10.30	oa			1.70					322	36.0	
PC61	Austal	41.75			12.50	mld			1.60					358	35.0	
PC22d	AMD / Dakota Creek	41.30			11.50	oa			1.50		40			325		36.0
PC62	AMD / Dakota Creek	43.70			12.00	oa			1.50		40			358		37.0
PF5b	Hitachi	39.50			11.40	mld	3.70	mld	1.90	w/o			284	200		45.0
PC63	Austal	47.60		41.60	13.00	mld	4.00	mld	1.40	w/o	54			330	38.0	
PC4f	Austal	40.10		35.00	10.80	mld			1.40	w/o				302	35.0	
PC64	Sabre	25.49		21.92	8.00	oa			1.80					229	28.0	30.0
PC65	Austal	52.40		45.40	13.00	mld			1.50					366	34.0	

Propulsion Plant / kW	Range (n.m.)	Fuel (lt)	Fresh Water (lt)	G.A.	DWT	Source	Other Capacities / Weights	Other			
D 4 ~ 2022						FF / XI '97					
D 4 x 625				*		FF / XII '97	cargo 12 + 2				
D 2 x 1260 + D 2 x 1680		1800		*		FF / XII '97					
D 2 x 2040				*		FF / XII '97					
D 2 x 1980		13400	1500	*		FF / XII '97					
D 4 x 1100	400	2 x 5300	1 x 380	*		FF / I-II '98	sul 1 x 380	B_H 2.75			
D 4 x 955		2 x 4960		*		FF / I-II '98		B_H 2.75			
D 4 x1300		2 x 4960		*		FF / Nov'98		B_H 2.75			
G 2 ~ 5970				*		FF / III '98					
D 4 x 2320						FF / III '98					
D 2 x 1740		7000	1200			FF / III '98		E 10			
D 2 x 2320		8800	1900			FF / III '98		E 10			
D 2 x 1500		2 x 3700	1 x 1000	*		FF / III '98					
D 2 x 2320				*		FF / V '98					
D 4 x 1194		13600	3000	*		FF / V '98					
D 4 x 1343		13600	1100	*		FF / V '98					
D 4 ~ 2023				*		FF / V '98					
D 4 x 1980		16500		*		FF / V '98					
D 2 x 1980				*		FF / V '98					
D 2 x 1350	400	6000	1000	*		FF / Oct'98					
D 4 x						FF / Nov'98					

// PC-4b

									306 + 86 up						
									248 + (100+6) up						
									232 + (112+8) up						
									70 + (29+48) up						
									184 + ((90+30)+70) up						
									184 + ((90+30)+70) up						
									248 + (52+4) up						
									388 + (80+48) up						
									238 + 84 up						
									199 + 159 up						
									212 + (92+21) up						
									218 + (132+8) up						
									170 + 30 up						
									196 + (54+80) up						
									252 + 50 up						
									169 m + 60 up						
									256 m + 90 up + 20 vip						

pax distribution

Ship Code	Des./Cons.	L_{OA} (m)	L_{BP} (m)	L_{WL} (m)	B (m)		D (m)		T (m)	DWT (t)	Δ (t)	GRT	Pax	V_S (kn)	V_M (kn)
PM1	Westport	28.90		24.55	6.90				1.65				149	28.0	
PM2	WaveMaster	33.00		28.40	6.50		1.80		1.80				200	32.5	
PM3	Pelmatic	31.00	26.50	*26.50*	6.50	mld			1.20				149	34.0	
PM4	Pelmatic	48.00	39.50	*39.50*	7.90	mld			1.30				450	36.0	
PM5	Oceanfast	31.90		27.70	6.50		1.90	mld	1.00				228	28.0	30.0
PM6	Oceanfast	40.00		34.60	9.50		3.50	mld	1.10				340	34.0	36.0
PM7	WaveMaster	35.40		31.60	7.00	mld	2.85	mld	2.10		85		260	27.0	
PM8	WaveMaster	31.50		26.60	6.50	mld	2.50	mld	0.90				196	28.0	
PM9	Aluminium Craft	35.00		*30.12*	7.40		2.90						250	27.0	
PM10	Aluminium Craft	37.00		*31.84*	8.00		3.70						350	30.0	
PM11	Aluminium Craft	32.00		28.50	7.40		2.75		1.25			229	275	25.0	26.0
		1.162													
PM12a	Almaz/Agat/Sukhoi	54.00			9.00		5.00						400	50.0	
PM12b	Almaz/Agat/Sukhoi	54.00			9.00		5.00						400	55.0	
PM12c	Almaz/Agat/Sukhoi	54.00			9.00		5.00						400	60.0	
PM13	Marinteknik	35.00			7.50				1.20				200	32.0	
PM14	Penguin	34.00			7.40		3.00		1.35				230	32.0	
PM15	FBM	70.00		65.00	13.50				2.00				650-800	33.0	35.0
PM16	FBM	45.00		42.00	8.80				1.50				500		35.0
PM17	FBM	35.00		32.65	7.00				1.1-1.8				170-210		33.0
PM18	Semo	28.00	25.50		7.20	oa	2.53		1.22				194	32.0	37.0
PM19	Rodriquez	50.46		43.00	9.20	oa	4.20		1.35	57	183.6		511		29.0
PM20	Lürssen-Werft	69.80	62.00		10.40		4.80		2.00				925	38.0	
PM21	Derecktor / NGA	32.50			8.50				1.20				100	35.0	
PM22a	Derecktor / NGA	36.40			8.50				1.60				150	30.0	
PM22b	Derecktor / NGA	36.40			8.50				1.60				150	40.0	
PM23	Covestar	33.50		28.42	6.85	oa			1.32				260	28.0	
PM24	WaveMaster	30.30		25.20	6.50	mld	3.80	mld	0.95				191		30.0
PM25	Westport	30.50			6.90	mld							150		

13 PM- 1a

Propulsion Plant / kW	Range (n.m.)	Fuel (lt)	Fresh Water (lt)	G.A.	DWT	Source	Other Capacities / Weights	$Fn_{S/WL}$	$Fn_{M/WL}$	L_{OA} / B	L_{WL} / B	A_S (m^2)
D 2 x 1287		11350	1 x 1130	*		FF / I-II '95		0.928		3.98	3.56	95
D 2 x 1240	450	10000	1000	*		FF / III '95		1.002		3.85	4.37	114
2 x 1500		3000	450			FF / IV '95		1.085		4.77	4.08	
3 x 2000		13000	1500			FF / IV '95		0.941		6.08	5.00	
D 3	150	6000	1000	*		FF / VII-VIII '95		0.874	0.936	4.91	4.26	130
D 2	300	10000	1500	*		FF / VII-VIII '95		0.949	1.005	4.21	3.64	254
D 2 x 970	420	5800	600	*		FF / XII '95	sullage 600	0.789		5.06	4.51	184
D 3 x 660	360	6000	1000	*		FF / XII '95		0.892		4.85	4.09	106
D 3						FF / I-II '96		0.808		4.73	4.07	
D 2 x 1940						FF / I-II '96		0.873		4.63	3.98	
D 3 x 620	180	2 x 2000	1 x 1000	*		FF / I-II '96		0.769	0.800	4.32	3.85	159
										4.67	4.13	
D 4 x 2000	400	15000	1500			FF / III,IV '96						
D 2 x 5000	400	22000	1500			FF / III,IV '96						
D 2 x 5600	400	23000	1500			FF / III,IV '96						
D 3 x 735				*		FF / XII `96						
D 4 x 610				*		FF / XII `96						
				*		SB / V `96						
D 2						F						
D 2/3						F						
D 2 x 1470		4500	1000	*		FF / IV '97						
D 2 x 2000		32000m^3				FF / VI '97						
D 4 x 3805	550			*		FF / V '97						
D 2 x 1500						FF / V '97						
D 2 x 610						FF / V '97						
D 4 x 610						FF / V '97						
D 2 x 735				*		FF / IX '97						
D 3 x 660	250	5600	1000	*		FF / IX '97	sul 750					
D 2 x 1950			1135			FF / V '98						

A_S/p (m^2)	A_P (m^2)	A_P/p (m^2)	A_P / A_S	B / T	L_{WL} * B	∇	$L_{WL}/\nabla^{1/3}$	pax distribution	
0.64	117	0.79	1.23	4.18	169.4	111.8	5.10		
0.57	131	0.66	1.15	3.61	184.6	132.9	5.56		
				5.42	172.3	82.7	6.08		
				6.08	312.1	162.3	7.24		
0.57	141	0.62	1.08	6.50	180.1	72.0	6.66		
0.75	314	0.92	1.24	8.64	328.7	144.6	6.59		
0.71	205	0.79	1.11	3.33	221.2	185.8	5.54		
0.54	136	0.69	1.28	7.22	172.9	62.2	6.71		
					222.9	0.0			
					254.7	0.0			
0.58	172	0.63	1.08	5.92	210.9	105.5	6.03		
0.62		0.73	1.17	5.66					
								178 + 22 up	
								200 + 30 up	
								92 + 42 aft + 60 up	
								106 + 290 mid + 115 up	
								158 dn + 428 + 339 up	
								172 + (76+12) up	
								116 + (13+62) up	
								102 + 48 up	

Ship Code	Des./Cons.	L_{OA} (m)	L_{BP} (m)	L_{WL} (m)	B (m)		D (m)		T (m)	DWT (t)	Δ (t)	GRT	Pax	Vehicles
VM1	Pelmatic	71.30	60.40	60.40	11.30	mld			2.10				450	43
VM2	Marinteknik	85.00		75.15	15.00				3.00	300			584	104
VM3	Pelmatic	100.00	87.50	87.50	17.30	mld			3.50				650	170 / 82+8
VM4	Pelmatic	125.00	114.50	114.50	17.30	mld			5.10				750	180 / 100+10
VM5a	Fincantieri	118.00	106.00	106.00	19.40	oa	11.80		3.40		2350		900	320 + 14
VM6a	Fincantieri	95.00	82.00	82.00	16.00		4.60		2.60	400+			600	173
VM7a	Bazan	124.70		109.80	18.70	oa	11.20		2.50		1810		1250	246 / 230 + 4
VM7b	Bazan	124.70		109.80	18.70	oa	11.20		2.50				1250	244
VM8	FFM / Rodriquez	141.84		122.70	21.10		12.20		3.11 / 3.43	706 / 1185	2700 / 3179		1500	425 / 170 + 30
VM9	JSC Meteor	100.00		86.00	16.40	oa			2.40	525	1250		540	112
VM10a	Mjellem & Karlsen	95.00	86.45	88.90	17.40	mld	6.00		3.65	500		4675/1402	626	160 / 52 + 12
VM10b	Mjellem & Karlsen	95.00	86.45	88.90	17.40	mld	6.00		3.60				600	160 / 52 + 12
VM10c	Mjellem & Karlsen	95.00	86.45	88.90	17.40				3.60	500		4000	600	160 / ? + 12
VM11a	Mjellem & Karlsen	115.00		101.68	17.40	mld	6.00		3.70				800	210 / 65 + 16
VM11b	Mjellem & Karlsen	115.00		101.68	17.40	mld	6.00		3.70				800	210 / 65 + 16
VM12	Mjellem & Karlsen	135.00		119.36	20.00	mld			4.10				1200	400
VM13a	Fincantieri	100.00	88.00	88.00	17.10	mld	10.70		2.75	340			800	175
VM14	Royal Schelde	128.00		115.00	18.40/18.00		7.00		2.80 / 4.00				778	234 / 166 + 6
VM15a	Fincantieri	82.00	72.00	72.00	14.00		8.50			170			450	70
VM15b	Fincantieri	82.00	72.00	72.00	14.00		8.50			170			450	70
VM16a	Fincantieri	96.50	83.80	83.80	16.00		10.50			320 / 400			650	175
VM16c	Fincantieri	96.00		-	16.20	mld	10.50		2.90	400			800	180 + 8
VM17	Fincantieri	143.10	128.60	128.60	22.00		12.60			775 / 930			1500	420+
VM18a	Royal Schelde	135.00		119.36	17.50				3.30	400			750	150 + 6
VM18b	Royal Schelde	135.00		119.36	17.50				3.30	400			750	150 + 6
VM19	Marinteknik	86.00		76.04	14.30		5.00		3.50				550	120 + 10
VM20	Bazan	129.00		115.35	21.50				2.90				1000	375
VM21	I H I	199.00		175.95	25.00								515	81 + 122
VM22	Schischau Seebeckwerft	173.70	158.00	165.40	24.00	mld	8.80		6.25	5240			1400	2245m
VM23	Rodriquez	101.75		85.30	14.50				2.12	233	1033		450	150
VM24a	Bazan	96.00		84.88	14.60						1070		450	116 / ? + 11
VM24b	Bazan	96.00		84.88	14.60						1070		600	84
VM24c	Bazan	96.00		84.88	14.60						1070		450	113
VM25	Bazan	122.50		108.31	18.70				2.40				750	170
VM26	Royal Schelde	90.00		78.25	15.00				2.10				400	144 / ? + 18
		1.131												

V_S (kn)	V_M (kn)	Propulsion Plant / kW	Range (n.m.)	Fuel (lt)	Fresh Water (lt)	G.A.	DWT	Source	Other Capacities / Weights	Other	$Fn_{S/WL}$
33.0 / 34.0		4 x 2300		25000	7500			FF / III '95			0.698/0.717
35.0	36.0	D 3	750			*		FF / IV '95			0.663
34.0		4 x 6000						FF / IV '95	FO 90 / FW 7.5		0.597
34.0		G 1 x 21000 + D 2 x 6000						FF / IV '95			0.522
40.0	42.0	G 2 x 21000 + D 2 x 600	500					FF / V '95			0.638
36.0		D 4 x 6000	300			*		FF / V '95			0.653
38.0	40.0	D 6 x 5800	300			*		FF / V '95	FO 70/450 / FW 8	A 2300	0.596
38.0		D 6 x 5650				*		NA / XI '95			0.596
36.0 / 34.0	35.5 / 37.5	G 1 x 21000 + D 4 x 600	290 / 300			P	*	FF / VI '95			0.534/0.504
55.0 / 60.0		G 4 x 15000	1300			*		FF / VII-VIII '95		E 26	0.974/1.063
35.0		D 4 x 5800		196000	27000	+		FF / IX '95	LO 7000 / sew 20000 / BW 183000		0.610
33.0	38.0	D 4 x 5800						FF / IX '95			0.575
33.0	35.0	D 4 x 5800				*		SB / VII-VIII '94			0.575
33.0		D 4 x 5800						FF / IX '95			0.538
40.0		G						FF / IX '95			0.652
30.0								FF / IX '95			0.451
37.8	40.0	D 4 x 6875				*		FF / XII '95			0.662
37.5		D 4 x 6875		85000	7000	*		FF / I-II '96	LO 3500 / sew 7000 / bilge 10000		0.574
32.0		D 2 x 5600						FF / I-II '96			0.619
39.0		D 4 x 4200						FF / I-II '96			0.755
31.5		D 4 x 5650						FF / I-II '96			0.565
35.0	37.0	6500 / D 4 x 7080 / D 4	300				400	FF / Oct'98			
36.8		D 2 + G 1 ~ 54000						FF / I-II '96			0.533
35.0		D 4 x 7380 / G 2 x 14800						FF / I-II '96			0.526
38.0		G 2 x 18900						FF / I-II '96			0.571
35.0		D 4						FF / I-II '96			0.659
	39.0	G 2 x 20800 + D 2 x 500	360 - 400			*		SB / V '94			
29.4		D 2 x 23850						NA / III '95			0.364
26.8		D 4 x 7920		1 350 000	300 000	*		NA / IV '95	DO 90000 / BW 1 270 000		0.342
43.0		G 1 x 20500 + D 2 x 356	370 / 680			*		SB / XI '93			0.765
34.0		D 4 x 5000						SB / V '94			0.606
34.0		D 4 x 5000						SB / V '94			0.606
41.0		G 1 x 20800 + D 2 x 5000						SB / V '94			0.731
	43.0	G 1 x 20800 + D 2 x 5000						SB / V '94			
37.0		D 4 x 6000				*		SB / I-II '95			0.687

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$Fn_{M/WL}$	L_{OA} / B	L_{WL} / B	A_S (m^2)	A_S/p (m^2)	A_P (m^2)	A_P/p (m^2)	A_P / A_S	A_V (m^2)	A_V/v(m^2)	B / T	L_{WL} * B	pax distribution	$L_{WL}/\nabla^{1/3}$	∇	$L_{WL}/\nabla^{1/3}$
	6.31	5.35								5.38	682.5			573.3	7.27
0.682	5.67	5.01	680	1.16	787	1.35	1.16	1393	13.39	5.00	1127.3			1352.7	6.80
	5.78	5.06								4.94	1513.8			2119.3	6.81
	7.23	6.62								3.39	1980.9			4040.9	7.19
0.670	6.08	5.46								5.71	2056.4		8.04	2796.7	7.52
	5.94	5.13	523	0.87	863	1.44	1.65	1685	9.74	6.15	1312.0			1364.5	7.39
0.627	6.67	5.87	1172	0.94	1437	1.15	1.23	2377	9.66	7.48	2053.3		9.08	2053.3	8.64
	6.67	5.87	1494	1.20	2026	1.62	1.36	2377	9.74	7.48	2053.3			2053.3	8.64
0.526/0.556	6.72	5.82								6.78/6.15	2589.0		8,88/8,41	3220.7	8.31
	6.10	5.24	941	1.74	1279	2.37	1.36	1556	13.89	6.83	1410.4		8.05	1354.0	7.77
	5.46	5.11	647	1.03	917	1.46	1.42	1959	12.24	4.77	1546.9			2258.4	6.78
0.662	5.46	5.11								4.83	1546.9			2227.5	6.81
0.610	5.46	5.11	789	1.32	972	1.62	1.23	1959	12.24	4.83	1546.9			2227.5	6.81
	6.61	5.84								4.70	1769.2			2618.5	7.38
	6.61	5.84								4.70	1769.2			2618.5	7.38
	6.75	5.97								4.88	2387.2			3915.0	7.57
	5.85	5.15								6.22	1504.8			1655.3	7.44
	7.03	6.32	843	1.08	1190	1.53	1.41	2820	12.05	6.50	2093.0			2318.4	8.69
	5.86	5.14									1008.0				
	5.86	5.14									1008.0				
	6.03	5.24									1340.8				
	6.50	5.85									2829.2				
	7.71	6.82								5.30	2088.8			2757.2	8.51
	7.71	6.82								5.30	2088.8			2757.2	8.51
	6.01	5.32								4.09	1087.4			1522.3	6.61
0.596	6.00	5.37	1140	1.14	1584	1.58	1.39	4225	11.27	7.41	2480.0			2876.8	8.11
	7.96	7.04									4398.8				
	7.24	6.89								3.84	3969.6			9924.0	7.70
	7.02	5.88	503	1.12	690	1.53	1.37	1449	9.66	6.84	1236.9		8.51	1048.8	8.40
	6.58	5.81									1239.2		8.37		
	6.58	5.81									1239.2		8.37		
	6.58	5.81									1239.2		8.37		
0.679	6.55	5.79								7.79	2025.4			1944.4	8.68
	6.00	5.22	499	1.25	677	1.69	1.36	1450	10.07	7.14	1173.8			986.0	7.86
	6.43	5.70		1.17		1.58	1.36		11.27	5.66					

Ship Code	Designer / Constructor	Loa (m)	Lpp (m)	Lwl (m)	B (m)		D (m)		T (m)	DWT (t)	Δ (t)	GRT	Pax	Vehicles
VM27a	Fincantieri	146.00	128.60	128.60	22.00		12.60		3.60	800 / 1200			1800	460 / 30
VM28	Leroux & Lotz	102.00		87.50	15.00	mld	5.20		2.40/3.70	200 - 320	1100		500	148 / 108 + 4
VM29	Leroux & Lotz	137.00		122.50	21.00	mld	6.20		/3.20	750			1000	308 / 290 + 6
VM30	Rodriquez	103.50		87.00	14.50	oa	9.50		2.30	280	1170		507	150 / 132 + 3
VM7c	Bazan	124.70		109.80	18.70	oa	6.20		2.44		1840		1250	238 / 217 + 4
VM15c	Fincantieri	82.00	72.00	72.00	14.00		9.25		2.20				600	70
VM5b	Fincantieri	120.00	106.00	106.00	19.00	oa	11.50		3.50	850			900	310 + 360m
VM5c	Fincantieri	120.00	106.00	106.00	19.00	oa	11.50		3.50	850			900	310 + 360m
VM6b	Fincantieri	94.00	82.00	82.00	16.50	oa	10.25		2.70	260			450 - 600	150
VM6c	Fincantieri	94.00	82.00	82.00	16.50	oa	10.25		2.70	245			450 - 600	150
VM6d	Fincantieri	94.00	82.00	82.00	16.50	oa	10.25		2.70	245			450 - 600	150
VM31	Finnyards	150.00			20.00				4.00	1500			600	100 + 30
VM32a	Fincantieri	128.00	112.20	112.20	19.40	mld	12.20			600			1000	300 + 8
VM32b	Fincantieri	128.00	112.20		19.40	mld	12.20			600			1200	300 + 12Coach
VM33	Finnyards	100.00	89.40	89.40	16.00	mld	6.10		3.00	310 / 450			600	160 / 116 + 6
VM34	Leroux & Lotz	66.00	58.00	58.00	10.90	mld			2.00	92-120			450	42
VM35	Leroux & Lotz	72.00			11.10				2.10	102-130			450	50
VM36	Samsung	99.50											630	160
VM37	Leroux & Lotz	112.00	100.00		15.00	mld	5.40		2.50	360-450			700	140 / 108 + 8
VM7d	Bazan	125.00	110.00		18.70		11.30		2.70	448-574			1200	219 / 90 + 13 / 110 + 15
VM38	Finnyards	100.00			16.40				3.00	310			600	160 / 116 + 6
VM39	C. M. N.	73.00			13.00	oa			2.00				500	15
VM40	Rodriquez	70.90		64.00	12.40	oa	8.60		2.45	200	625		550	57 / 40 + 3
VM13b	Fincantieri	100.00	88.00		17.10	mld	10.70		2.60				782	175
VM41	Samsung	99.50											630	160
VM27b	Fincantieri	145.60	128.60		22.00		12.60			805-1200	(freight)	10200	1800	450 / 100 + 30
VM42	Fincantieri	112.00			17.10	mld	11.00		3.00				1000	200 + 10Van

Vs (kn)	VM (kn)	Propulsion Plant / kW	Range (n.m)	Fuel (lt)	Fresh Water (lt)	G.A.	DWT	Source		Other	Fn s/WL
40.0		G 2 x 21000 + D 4 x 650(	300					FF / III,IV '96			
37.0		D 4 x 6000/6500	300 / 700	84000	8000	*		FF / VII-VIII '96			
42.0		G 2 x 25000 + D 2 x 6000		130000	16000	*		FF / VII-VIII '96			
35.0	37.0	D 4 x 6000		89000		*	*	FF / IX '96			
38.0		D 6 x 5650	300 / 1700	0000/490000		*	*	FF / XII `96			
40.0	44.0	D 4 x 4000	300			P		B			
40.0		G 2 + D 2 ~ 54000	300 - 500			*		D			0.638
33.0		D 6 x 6000	300 - 500			*		D			0.527
40.0		G 1 + D 2 ~ 28200	300 - 500			*		D			0.726
36.0		D 4 x 6000	300 - 500			*		D			0.653
33.0		D 4 x 5250	300 - 500			*		D			0.599
35-40		D 6 x 7000						FF / IV '97			
40.0	42.0					*		F			
42.0	40.0	/ D 2 x 19500 / G 1 + D 4 / G 2 + D 2					600	FF / Oct'98			
34.0		D 4 x 6500						F			
30.0		D 4		26000	8000	*		F			
32.0		D 4 ~ 10300		30000	10000	*		F			
35.0		D 4 x 7080				*		NA / VI '97			
35.0		D 4 x 7080	500			*		FF / IV '97			
36.5		D 6 x 5650	300			*	*	FF / IV '97			
35-40		D 4 x 6500						FF / IV '97			
34-37		D 4 x 3250-4000				*		FF / VI '97		cargo 100m	
	35.0	D 4 x 2350	280	46000				FF / VI '97			
38.0	40.0	D 4 x 6875				*	*	FF / VI '97			
	35.0	D 4 x 7080						SB / XI '97			
40/33/22	(4+2/4+1/4	G 2 x 21000 + D 4 x 6500				*	*	FF / VII-VIII '97			
42.0	44.0	080 / D 4 x 7200 / G 1 x	300					FF / Oct'98			

	L_{OA}/B	L_{WL}/B								B/T	$L_{WL} \cdot B$	pax distribution	$L_{WL}/\nabla^{1/3}$	∇	$L_{WL}/\nabla^{1/3}$
														2716.0	9.22
												432 + 68	8.55	1260.0	8.10
														3292.8	8.23
												c 32+80+38	8.32	1160.6	8.28
												828 + 422 up			
	6.32	5.58								5.43	2014.0			2819.6	7.50
	6.32	5.58								5.43	2014.0			2819.6	7.50
	5.70	4.97								6.11	1353.0			1461.2	7.23
	5.70	4.97								6.11	1353.0			1461.2	7.23
	5.70	4.97								6.11	1353.0			1461.2	7.23

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Ship Code	Des./Cons.	L_{OA} (m)	L_{BP} (m)	L_{WL} (m)	B (m)		D (m)		T (m)	S (m)	DWT (t)	Δ (t)	GRT	Pax
VC1a	Incat Australia	70.40		*63.94*	19.50	oa			2.20					450
VC1b	Incat Australia	70.36		63.90	19.50	oa	5.65		2.10	13.75	142 (112)			294
VC1c	Incat Tasmania / A.M.D	71.00		*64.49*	19.50	oa			2.20					450
VC2a	Incat Australia	78.00		*71.37*	19.50	oa			2.10					750
VC2b	Incat Australia	78.40		71.94	19.50	oa			2.18		(742)? (123)			750
VC2c	Incat Tasmania / A.M.D.	78.00		*71.37*	19.50	oa								750
VC2d	A.M.D. / Incat	78.70		*72.01*	19.50	oa					123			769
VC2e	Incat Australia / A.M.D.	79.25		72.30	19.50	oa			2.16		123			769
VC3	Royal Schelde	76.60		68.00	22.15	oa	7.20	trucks	3.00 / 3.25	10.45	360			620
VC4a (S)	Danyard	76.10		*62.95*	23.40	mld			3.36		250			450
VC5	WaveMaster	52.50		45.90	16.80	mld			2.00					450
VC6	Westamarin	58.00		49.80	16.80	mld	5.90	mld	2.60	13.00			2000	600
VC7	Westamarin	75.00		64.35	25.50	mld	9.20	mld	3.40	19.65			4000	964
VC8a	Kvaerner Fjellstrand	60.00		54.65	16.50	oa	5.70	mld	2.15		140			450
VC9	Kvaerner Fjellstrand	60.00		*52.77*	19.90	oa	6.67	mld	2.10		170			450
VC10	Incat Designs	85.58		80.53	23.20				3.00		372.7			794
VC11	JSC Meteor	120.00		*105.54*	36.00	oa			2.60		1433	3500		1500
VC12	Mitsui	50.00		*43.98*	14.00	oa							380	300
VC13	Mitsui	56.00		*49.25*	17.00	oa							699	350
VC14	Mitsui	83.00		*73.00*	19.20	oa							1400	400
VC15	Mitsui	88.00		*77.40*	21.60	oa							2200	400
VC16	Kvaerner Fjellstrand	59.20		54.00	16.50				2.90					437
VC17	Oceanfast	44.00		40.10	12.50		3.70	mld	1.50					255
VC18	Oceanfast	44.70		41.10	12.50		3.70	mld	2.20					404
VC19	Oceanfast	55.00		48.30	15.00		4.30	mld	1.50					296
VC20	Oceanfast	59.00		51.30	18.50		4.30	mld	1.80					296
VC21a (S)	Ferries Australia	82.30		69.00	23.00	mld	6.50	mld	2.50 / 3.20	13.85				600
VC22a	Incat Australia	58.10		52.80	14.46	oa			1.80		77.1 / 102.4			351
VC22b	Incat Australia	58.10		52.80	14.46	oa			1.80		77.1 / 102.4			351
VC22c	Advanced Multihull Designs	59.43		52.80	14.46	mld			1.40		76.6 / 102.4			351
VC23a	Ferries Australia	78.60		68.50	23.00	mld			2.50 / 3.10	17.35	300		4859	600
VC23b	Austal	78.60		68.50	23.00	mld	7.00	mld	2.40	18.90				600
VC23c	Ferries Australia	78.60		68.50	23.00	mld			2.40	19.10	150 / 350			600
VC24a	Ferries Australia	95.00		88.80	27.00	mld	7.50	mld	2.50 / 3.20					1000
VC24b	Ferries Australia	93.60		78.90	27.00	mld			2.50	21.80	250 / 500			1000
VC25	WaveMaster	44.00		38.60	12.00				1.75 / 2.40	8.75				236
VC26a	Incat Designs	122.00		96.20	24.80				3.80		531			1000
VC27 (W)	Daewoo	40.25		*35.40*	9.30	mld			1.50					280
VC28	Daewoo	78.00		*68.60*	16.40									600

Vehicles	V_S (kn)	V_M (kn)	Propulsion Plant / kW	Range (n.m.)	Fuel (lt)	Fresh Water (lt)	G.A.	DWT	Source
63		55.0	D 4 x 5310						FF / I-II '95
53	45.0	50.0	D 4 x 5420				*	*	FF / III '95
65		55.0	D 4 x 5310						SB / I-II '95
32	47.0	51.0	D 4 x 5420						FF / I-II '95
30	47.0	50.0	D 4 x 5420					*	FF / III '95
32	47.0	51.0	D 4 x 5310						SB / I-II '95
32	50.0	52.7	D 4 x 5420		35000	2500			SB / XI '95
32	49.0	53.0	D 4 x 5420	300	35000 / 100000	2000	*	*	FF / XII '95
52 / 115 + 110m / 90 + 160n	36.0		D 4 x 5700	300	92000	4000			FF / IV '95
120	43.6	46.4	G 2 x 12400	240	2 x 25000	2 x 5000	*		FF / IV '95
46	32.0		D 4 x 1940		30000	16000	P		FF / IV '95
54	37 - 43		11000 - 16000		20000	3000	*		FF / IV '95
187 / 159 + 8	35 - 40		22000 - 30000		40000	6000	*		FF / IV '95
52 / 44 + 2	30 - 45		D 2 / D 4 / G 2				P		FF / VI '95
94 / 42 + 6	30 - 45		D 2 / D 4 / G 2						FF / VI '95
190 / 175 + 4	36.0	39.0	D 4 x 5500	350			P	*	FF / VI '95
400 + 40	37.0	40.0	G 4 x 15000	700					FF / VII-VIII '9
30	40.0		4 x 2647						FF / VII-VIII '9
44 / + 13	31.0		2 x 3897						FF / VII-VIII '9
60	42.0		4 x 3897						FF / VII-VIII '9
80 / + 21	36.0		4 x 3897						FF / VII-VIII '9
46	33.0		D 2 x 5400		2 x 15000	1 x 3000	*		FF / VII-VIII '9
12 + 15 containers	28.0	30.0	D 2	200	14000	1500			FF / VII-VIII '9
18	28.0	30.0	D 2	200	14000	1500			FF / VII-VIII '9
31	35.0	37.0	D 4	350	22000	1500			FF / VII-VIII '9
70 / 38 + 6	30.0	32.0	D 4	450	35000	5000			FF / VII-VIII '9
175 / 124 + 4 / 34 + 10	36.0		D 4 x 6000		2 x 30000	2 x 2000	*		FF / IX '95
30	36.0		D 2 x 4320		18000	2000		*	FF / XII '95
42	34.0		D 2 x 4320		18000	2000		*	FF / XII '95
30 (42)	39.0		D 2 x 5420	100	2 x 4200 / 18000	2000		*	FF / I-II '96
163 / 38 + 10	34.0		D 4 x 5500		2 x 30000	2 x 2000	*		FF / XII '95
184			D 4		2 x 30000	2 x 2000	*		D
184 / 64 + 10	40.0 / 36.0	42.0 / 38.0	D 4 x 5500				*		D
241 / 94 + 12					2 x 40000	2 x 3000			FF / XII '95
252 / 102 + 12	37.0 / 34.0	39.0 / 36.0	D 4 x 6000				*		D
10 + 24t cargo	28.0	29.0	D 2 x 2000	540			*		FF / XII '95
250	37.0		D 4					*	FF / XII '95
8	38.0	40.0	D 2 x 2000						SB / I-II '95
60	35.0		D 2 x 5420						SB / I-II '95

Other Capacities / Weights	Other	$Fn_{S/WL}$	$Fn_{M/WL}$	L_{OA} / B	L_{WL} / B	S / L_{WL}	A_S (m^2)	A_S/p (m^2)	A_P (m^2)	A_P/p (m^2)	A_P / A_S	A_V (m^2)
			1.130	3.61	3.28							
	B_H 5.00	0.925	1.027	3.61	3.28	0.22	373	1.27	642	2.18	1.72	536
			1.125	3.64	3.31							
		0.914	0.992	4.00	3.66							
		0.910	0.968	4.02	3.69							
		0.914	0.992	4.00	3.66							
		0.968	1.020	4.04	3.69							
sullage 2500 / DO 1000	B_H 5.00	0.947		4.06	3.71		667	0.87	1011	1.31	1.52	400
LO 500 / sew 4000	B_H 6.30	0.717		3.46	3.07	0.15	726	1.17	987	1.59	1.36	2017
FO 36 / FW 10			0.961	3.25	2.69		782	1.74	1314	2.92	1.68	1469
		0.776		3.13	2.73							
		0.861 - 1.001		3.45	2.96	0.26	386	0.86	669	1.49	1.73	655
		0.717 - 0.819		2.94	2.52	0.31	984	1.02	1292	1.34	1.31	2183
		0.667 - 1.000		3.64	3.31							
		0.678 - 1.018		3.02	2.65							
		0.659	0.714	3.69	3.47							
	E 20	0.592	0.640	3.33	2.93							
		0.991		3.57	3.14							
		0.726		3.29	2.90							
		0.807		4.32	3.80							
		0.672		4.07	3.58							
LO 1 x 1000 / sew 1 x 3000 / sludge 1 x 500		0.738		3.59	3.27		358	0.82	498	1.14	1.39	648
		0.726	0.778	3.52	3.21							
		0.717	0.769	3.58	3.29							
		0.827	0.875	3.67	3.22							
		0.688	0.734	3.19	2.77							
	B_H 5.05	0.712		3.58	3.00	0.20	815	1.36	1118	1.86	1.37	2144
LO 1000 / DO 1000 / sullage 2500	B_H 4.00	0.814		4.02	3.65							
LO 1000 / DO 1000 / sullage 2500	B_H 4.00	0.769		4.02	3.65							
LO 1000 / bilge 200 / sullage 2000	B_H 4.00	0.882		4.11	3.65		270	0.77	380	1.08	1.41	476
	B_H 5.05	0.675		3.42	2.98	0.25	534	0.89	943	1.57	1.77	1344
	B_H 4.25			3.42	2.98	0.28	541	0.90	931	1.55	1.72	1205
		0.794 / 0.715	0.834 / 0.754	3.42	2.98	0.28	599	1.00	871	1.45	1.45	1286
				3.52	3.29							
		0.684 / 0.629	0.721 / 0.666	3.47	2.92	0.28	1232	1.23	1665	1.67	1.35	3155
	cc 85 / B_H 3.25	0.740		3.67	3.22	0.23	192	0.81	241	1.02	1.26	129
	lane 1325	0.620		4.92	3.88							
		1.049	1.104	4.33	3.81							
		0.694		4.76	4.18							

$A_V/v (m^2)$	B / T	L_{WL} * B	pax distribution	B_H / T	L_{WL} / B_H		$L_{WL}/\nabla^{1/3}$	∇	$L_{WL}/\nabla^{1/3}$
	8.86	1246.8							
10.11	9.29	1246.1		2.38	12.78	5.00		536.8	9.91
	8.86	1257.6							
	9.29	1391.7							
	8.94	1402.8							
		1391.7							
		1404.2							
12.50	9.03	1409.9		2.31	14.46	5.00		624.7	10.66
13.27	7.38	1506.2		2.10	10.79	6.30		1028.2	8.49
12.24	6.96	1473.0							
	8.40	771.1							
12.13	6.46	836.6							
11.67	7.50	1640.9							
	7.67	901.7							
	9.48	1050.1	(cars) 68 + 26 up						
	7.73	1868.3							
	13.85	3799.4					8.83		
		615.7							
		837.3							
		1401.6							
		1671.8							
14.09	5.69	891.0							
	8.33	501.3	110 + 145 up						
	5.68	513.8	262 + 142 up						
	10.00	724.5	296 up						
	10.28	949.1	296 up						
12.25	9.20	1587.0		2.02	13.66	5.05		696.9	9.81
	8.03	763.5		2.22	13.20	4.00		304.1	9.89
	8.03	763.5		2.22	13.20	4.00		304.1	9.89
11.33	10.33	763.5		2.86	13.20	4.00		236.5	10.76
8.25	9.20	1575.5		2.02	13.56	5.05		691.9	9.76
6.55	9.58	1575.5		1.77	16.12	4.25		559.0	10.48
6.99	9.58	1575.5							
	10.80	2397.6							
12.52	10.80	2130.3							
12.90	6.86	463.2	66 up + 30 up1 +	1.86	11.88	3.25		175.6	8.68
	6.53	2385.8							
	6.20	329.2							
		1125.0	114 + 166 up						

Ship Code	Designer / Constructor	Loa (m)	Lpp (m)	LWL (m)	B (m)		D (m)		T (m)	S (m)	DWT (t)	Δ (t)	GRT	Pax
VC29	Art Anderson Associates	45.00		40.25	12.40				2.00	9.05				375
VC30	Austal	75.60		66.85	23.00	mld			2.20 / 4.00			850		400
VC31a	Austal	59.90		50.30	18.00	mld	5.50	mld	2.00	14.40				442
									ride control					
		1.137												
VW1	Kawasaki	99.78		88.93	19.98	mld	7.30		3.10	14.40	570		2200	460
VW2	Incat Australia	81.15		66.30	26.00				3.00	21.90	310	1050		677
VW3	Incat Australia	83.85		71.63	26.00				3.05		330	1150		777
VW4	Incat Designs	92.90		83.40	29.62				3.27	24.65	409			800
VW5	Incat Designs	78.21		73.46	19.10				2.50		190			452
VW6	Samsung	80.00		77.55	19.50									600
		1.121												
VS1	Mitsui	39.50		*31.57*	13.20	oa							570	200
VS2	Mitsui	64.00		*51.16*	20.00	oa							1600	400
VS3	NQEA	81.00		*64.75*	23.40				3.40		330			600
VS4	NQEA	109.00		85.30	31.50				4.40	25.15	600			1100
VS5 (C)	Ferries Australia	82.00		68.15	23.00				2.20 / 3.00	17.90				600
VS6	Schischau Seebeckwerft	54.60		47.40	23.40						250			600
VS7	NTUA	51.50		37.60	31.70		9.46		5.00	24.40	226	1060	2544 / 763	752
VS8	NTUA	58.00		46.25	31.40		9.50		4.92	24.40	314	1051		500 - 696
VS9	Finnyards / Stena	126.60	107.50		40.00	mld	12.50		4.5		1500			1500
									ride control					
		1.251												
VSE1	Oceanfast / Ulstein	55.00		48.15	15.00		4.30	mld	1.50					300
		1.142												
VC32a	Marinteknik	55.00		*48.37*	15.00				2.00					440
VC33	Almaz/Agat/Sukhoi	74.00		*65.08*	25.00	oa	4.00							850
VC34	Almaz/Agat/Sukhoi	80.00		*70.36*	23.00	oa	4.00							800

Vehicles	V_S (kn)	V_M (kn)	Propulsion Plant / kW	Range (n.m.)	Fuel (lt)	Fresh Water (lt)	G.A.	DWT	Source
28 / 20 + 4	30.0		D 2 x 2700				*		SB / XI '95
72 + 10	40.0				20000	2000	*		D
109 / 85 + 4			D 2		35000	3000	*		D
94 / + 24	30.0		D 2 x 5420 + D 2 x 4060				*		FF / III '95
181	37.0		D 4 x 5500		2 x 16400 / 2 x 104200	5400	*	*	FF / XII '95
200 / 128 + 4	38.0		D 4 x 6875		2 x 16400 / 2 x 104200	5400		*	FF / XII '95
225 / 197 + 5	37.0	39.0	D 4 x 6190				*	*	FF / XII '95
72 / 52 + 3	49.0	52.0	D 4 x 6500					*	FF / XII '95
55	35.0		D 4 x 5000				*		FF / V '95
20	32.0		2 x 3897						FF / VII-VIII '95
62 / + 15	31.0		4 x 5368						FF / VII-VIII '95
180	40.0		G 2						FF / XII '95
320 / ? + 8	40.0		G 2				PS		FF / XII '95
175 / 124 + 4 / 34 + 10	36.0		D 4 x 6000				*		SB / XI '95
90 / 75 + 4	36.0		G 2 x 10000				*		SB / XI '93
84	30.0		D 4 x 3676	360			*	*	D
100	40.0	42.5	G 2 x 14915	500			*	*	D
375 / 120 + 50	40.0		G 2 x 13500 + G 2 x 20500		224000	20000	*		FF / III,IV '96
31	35.0	37.0	D 4	350	22000	1500	*		FF / III '95
42 / 34 / 27 + 3	32.0		D 4 x 2000	180	12000		*		FF / III,IV '96
220 / 176 + 8	36.0		D 2 x 6500	300					FF / III,IV '96
200 / 167 + 8	45.0		G 2 x 25000	400					FF / III,IV '96

Other Capacities / Weights	Other	$Fn_{S/WL}$	$Fn_{M/WL}$	L_{OA}/B	L_{WL}/B	S/L_{WL}	$A_S(m^2)$	$A_S/p\ (m^2)$	$A_P(m^2)$	$A_P/p\ (m^2)$	A_P/A_S	$A_V(m^2)$
	B_H 2.05	0.777		3.63	3.25	0.22	382	1.02	494	1.32	1.29	395
		0.804		3.29	2.91		503	1.26	673	1.68	1.34	1112
	B_H 3.75			3.33	2.79	0.29	386	0.87	681	1.54	1.76	750
				3.68	3.26	0.25		1.05		1.57	1.50	
	B_H 5.60	0.523		4.99	4.45	0.16						
LO 2 x 470 / sullage 2 x 2000 / EDO 500	L_H 61.45 / B_H 4.33	0.746		3.12	2.55	0.33	712	1.05	890	1.31	1.25	1947
LO 2 x 470 / sullage 2 x 2000 / EDO 500	L_H 72.20 / B_H 4.45	0.738		3.23	2.76							
	B_H 4.94	0.666	0.702	3.14	2.82	0.30	956	1.20	1519	1.90	1.59	2800
		0.939	0.997	4.09	3.85							
		0.653		4.10	3.98		585	0.98	807	1.35	1.38	874
		0.936		2.99	2.39							
		0.712		3.20	2.56							
	L_H 75.00	0.817		3.46	2.77							
	L_H 95.00 / B_H 5.35	0.711		3.46	2.71	0.29						
	B_H 5.15	0.716		3.57	2.96	0.26	815	1.36	1118	1.86	1.37	2144
		0.859		2.33	2.03		671	1.12	809	1.35	1.21	1599
	B_S 2.60 / L_H 50.00 / B_H 3.8(	0.804		1.62	1.19	0.65	481	0.64	540	0.72	1.12	751
	B_S 2.60 / L_H 50.00 / B_H 3.8(	0.966	1.027	1.85	1.47	0.53	926	1.85	1356	2.71	1.46	1425
DO11/LO13/sew16/sludge4/bilge15/BW1725		#DIV/0!		3.17	0.00							
		0.829	0.876	3.67	3.21							

14.11	6.20	499.1		1.03	19.63	2.05		132.0	9.96
15.44	10.45	1537.6					8.96		
6.88	9.00	905.4		1.88	13.41	3.75		301.8	9.45
11.37	8.59			2.06	13.83				
	6.45	1776.8		1.81	15.88	5.60			
10.76	8.67	1723.8		1.44	15.31	4.33	8.29		
	8.52	1862.4		1.46	16.10	4.45	8.69		
12.44	9.06	2470.3		1.51	16.88	4.94			
	7.64	1403.1	314 + 138 up						
15.89		1512.2							
		416.7							
		1023.2							
	6.88	1515.2							
	7.16	2687.0		1.22	15.94	5.35			
12.25	10.45	1567.5		2.34	13.23	5.15			
17.77		1109.2							
8.94	6.34	1191.9		0.76	9.89	3.80	4.68		
14.25	6.38	1452.3		0.77	12.17	3.80	5.78		
		0.0							
	10.00	722.3							
			146+242+52						
A_V/V (m²)	B/T	$L_{WL} \cdot B$	pax distribution	B_H/T	L_{WL}/B_H		$L_{WL}/\nabla^{1/3}$	∇	$L_{WL}/\nabla^{1/3}$

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VC-2d

Ship Code	Designer / Constructor	Loa (m)	Lbp (m)	Lwl (m)	B (m)		D (m)		T (m)	S (m)	DWT (t)	Δ (t)	GRT	Pax
VC35	Westamarin	81.10		*71.33*	27.00	mld	8.50		3.70		450			700
VC36	Westamarin	91.30		*80.30*	32.00	mld	10.50		4.00		600		9000	1000
VC37	Westamarin	103.30		*90.85*	32.00	mld	10.50		4.50		850		12000	1250-1500
VC38 (S)	Westamarin / Stena	88.00		*77.40*	30.00	mld	12.60		3.70		450		8650	900
VS10	Almaz/Agat/Sukhoi	53.20			19.20	oa	3.70				155			400
VC3b	Royal Schelde	76.60		68.00	22.15/21.75		7.20		3.6/(3/3.25)					600
VW2b	Incat Tasmania	81.15		66.30	26.00	oa			3.00		300	1100		693
VC21b	Ferries Australia	82.30		69.00	23.00	mld	6.50	mld	2.50/3.20				5333	600
VW7	Incat/Hitachi	62.00			15.40	mld	10.8/5.4	mld	2.30		140		860/835	296
VC39 (S)	Danyard	56.80		*49.96*	18.00	mld								325
VC4b (S)	Danyard	76.10		*66.93*	23.40	mld								450
VC4c (S)	Danyard	76.10		*66.93*	23.40	mld								550
VC4d (S)	Danyard	76.10		*66.93*	23.40	mld								600
VC40 (S)	Danyard	76.80		*67.55*	25.10	mld								600
VC41 (S)	Danyard	96.00		*84.43*	28.00	mld								750
VC4e (S)	Danyard	76.12			23.40		8.05				236			450
VC42a	Bazan / A.M.D.	77.34		69.96	19.46				2.15					450
VC43	IHI	153.50			27.50		8.50		3.50		750		11000	1000
VC44	IHI	199.90			29.80		10.50		4.90		2500		18000	500
VC45 (S)	RITS	110.00	105.00		36.00		14.50		4.50		1140	4100		1500
VC1d	Incat Tasmania / A.M.D.	70.40			19.50				2.15		142			436
VC46	A.M.D.	59.43			14.46	oa			1.60		130			350
VW8	A.M.D.	94.80			27.10				2.70		440			888
VW9	Incat	91.30		81.33	26.00				3.70		400			900
VC47	Finnyards	113.00		95.00	29.00	mld	10.00		3.90					1000
VC48	Finnyards	130.00			40.00	mld	12.50		4.40		1500			1500
VS11	SWATH International	75.50			31.00	oa			6.00					876
VS12	SWATH International	39.50			18.60	oa			3.80					550
VW10	Incat Tasmania	86.62		76.41	26.00	oa	6.75	mld	3.50			1165		776
VW11	A.M.D.	102.10		86.00	22.40	oa			3.00		450			1250
VC49	Finnyards	77.00			23.10				2.50		340			700
VC50	Finnyards	107.00			28.40				3.20		580			1100
VW9b	Incat Tasmania	91.30		81.30	26.00	oa	6.80	mld	3.70		400			876
VC51a	Kvaerner Fjellstrand	46.00			12.00	oa					57			360
VC51b	Kvaerner Fjellstrand	46.00			12.00	oa					57			220
VC52	Hyundai		80.00		20.80									800
VC53	Daewoo			70.00							328			600
VC54	Samsung	83.50			23.00									600
VC55	Austal	47.60		41.60	13.00	mld	4.00	mld	1.40		54			329
VC32b	Marinteknik	55.00			15.00	mld			2.00					400

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Vehicles	V_s (kn)	V_M (kn)	Propulsion Plant / kW	Range (n.m.)	Fuel (lt)	Fresh Water (lt)	G.A.	DWT	Source
200 / 155 + 10	32 - 43		D4 / G2 ~ 20000-34000	450	60000				FF / III,IV '96
270 / 220 + 12	40 - 46		G2 ~ 35000-52000	500	140000		*		FF / III,IV '96
310 / 240 + 14	36 - 45		G2 ~ 35000-52000	500	140000				FF / III,IV '96
212 / 154 + 10 / 140 + 70	40.0		G 2 x 17000	400	104000		*		FF / III,IV '96
60 / 40 + 3	35.0		D 2 x 6000	400	57600	3500	*		FF / III,IV '96
154 / 90 + 10	33.0 / 31.0	(36 LS)	D 4 x 5700	310	2 x 45000 m^3	4000 m^3	*	*	FF / VI '96
180	39.0	40.0	D 4 x 5500		2 x 16400 / 2 x 10420(	5400	*	*	FF / VI '96
175 / 124 + 4 / 34 + 10	37.5	40.2	D 4 x 6000	350	2 x 30000	4000	*	*	FF / VI '96
48 / 21+ 6	30.0	32.0	D 4 x 2023				*		FF / VI '97
60 / 52 + 2	34.0		D ~ 12400						FF / IX '96
120	43.6	46.4	G ~ 24800						FF / IX '96
110 / 95 + 4	42.5		D/G ~ 24800						FF / IX '96
110 / 95 + 4	41.0		D/G ~ 24800						FF / IX '96
180 / 142 + 4	40.0		G ~ 24800						FF / IX '96
240 / 220 + 6	42.0		G ~ 32000						FF / IX '96
120	40.8	46.4	G 2 x 12400						BWPV `97
52	57.0	60.0	G 2 x 16100		35000	2000	*		FF / XII `96
350	36.0		G 2 x 20600 + 2 x 5150	400					NA
100 x 12m	37.0		G 4 x 20600	300					NA
1270m / 320	40.0		G 4 x 17000						NA / IV '97
56	45.0	50.0	D 4 x 5420		35000	2000	*		F
52	40.0		D 4 x 5440		18000	2000	*		F
238	40.0	46.0	D 4 x 7200		70000	10000	*		F
240		43.0	D 4 x 7080		50000 / 292000		*		F
300 / 204 + 12	40.0		D 2 x 6000 + G 2 x 21500						F
375 / 108 + 50	40.0		G 2 x 21500 + G 2 x 14915						F
250 / 150 + 10	37.0		G 2 x 21500				*		F
31	26-34						*		F
200 / 182 + 4	40.0	44.0	D 4 x 7080		4 x 15250 / 2 x 24500(	5000	*	*	FF / III '97
244 / 217 + 6	42.0		D 4 x 7200 + 2 x 4060		70000	10000	*		FF / IV '97
180 / 130 + 8	35-40		D 4 x 6500						FF / IV '97
290 / 240 +14	35-40		D 2 x 6500 + G 2 x 17000						FF / IV '97
240 / 228 + 4	43.0		D 4 x 7080		56000 / 292000	5000	*		FF / IV '97
12		38.0	D 4 x 1740		2 x 10000	1 x 1500	*		FF / V '97
25		38.0	D 4 x 1740		2 x 10000	1 x 1500	*		FF / V '97
92		60.0					*		SB / XI '97
175 / 154 + ?	34.0		D 4 x 5650						SB / XI '97
175	38.0		D 4 x 6500						SB / XI '97
10		39.0	D 4 x 1980		16500		*		FF / VII-VIII '97
48	38.0		G 2 x 2840 + D 2 x 2000				*		FF / VII-VIII '97

Other Capacities / Weights	Other											
LO 2 x 500 / sew 4000 / bilge 2 x 7500 / slu 2 x 1000 (m^3)												
LO 2 x 470 / sul 2 x 2000 / EDO 500	L_{II} 67.3 / B_{II} 4.33											
WW 2000 / LO 2 x 300 / HO 2 x 100 / sew 2000												
lube 1000												
	B_{II} 4.33											
lube 2 x 820 / sul 5000 / em.gen. 2 x 850	B_{II} 4.33											
LO 1600 / sul 5000	B_{II} 4.30											
sew 1 x 1500 / slu 500												
sew 1 x 1500 / slu 500												

32 VC-3c

			436 + 257 up						
			284 + 12 up						
			70 + 380 up						
			450 + 326 up						
			838 + 412 up						
			470 + 406 up						
			145 + 162 up						
			145 + 162 up						
			340 + 60 up						

pax distribution

JJ VC- 3d

Ship Code	Designer/ Constructor	L_{OA}(m)	L_{BP}(m)	L_{WL}(m)	B(m)		D(m)		T(m)	S(m)	DWT(t)	Δ(t)	GRT	Pax
VC56	Mitsubishi	101.00			14.90		10.30		2.70				1498	423
VC31b	Austal	59.90		51.20	17.50	mld	6.65	mld	3.25/3.45		173			450
VC57	Ferries Australia	86.60		74.20	24.00		7.30	mld	3.20/4.10		340-400			800
VC58	CNM	43.10		40.10	10.40		4.10	mld	1.44		60			150
VC42b	Bazan / AMD	77.32		69.94	19.00	oa			2.13		142	721	1737	446
VC26b	CFI	122.50		96.00	25.80	oa			3.90		532			1000
VW12a	CFI	95.50		89.60	22.60	oa			2.90		432			770
VW13a	CFI	109.50		96.00	28.30	oa			3.90		544			1000
VC21c	Austal	82.30		70.70	23.00	mld	6.70	mld	2.80		340			900
VC59	IHI	72.09			12.90	mld	4.50	mld	2.05			204	1680	430
VW12b	Incat / CFI	95.50		89.60	22.60	oa			2.90		432			780
VW13b	Incat / CFI	109.50		96.00	28.30	oa			3.80		559			1000
VC51c	Kvaerner Fjellstrand	46.00			12.00	oa					50			308
VC60	Incat / Afai	80.10		72.30	19.00	oa			2.20		178			398
VC8b	Kvaerner Fjellstrand	60.00			16.50		5.85	mld	2.15/2.9		135			428

Vehicles	V_S (kn)	V_M (kn)	Propulsion Plant / kW	Range (n.m.)	Fuel (lt)	Fresh Water (lt)	G.A.	DWT	Source
106 / 78 + 5	35.0	42.0	D 4 x 6500				*		FF / IX '97
94 / 56 + 3	33.8	35.5	D 2 x 6500		24000	2000	*		FF / IX '97
200 / 84 + 10	37.0		D 4 x 6500	350	70000	4000	*	*	FF / IX '97
30	30.0		D 2 x 2088		13000		*		FF / XI '97
52		56.0	G 2 x 16100	200			*	*	FF / XII '97
314		37.0	26000						B
204		44.0	26000						B
227		42.0	36000						B
175	38.5	41.0	D 4 x 6500				*		SB / I-II '98
51 / 9		30.0	D 2 x 3925				*		FF / VI '98
223 / 204 + 4		44.0	D 4 x 6500				*		FF / VI '98
250 / 200 + 6		38.0	D 4 x 8250				*		FF / VI '98
12	38.0		D 4 x 2000		2 x 12000	1 x 1500	*		FF / VI '98
89		48.0	D 4 x 5500	440	4 x 12000	1 x 2500	*		FF / Oct'98
52 / 38 + 2	36.0		D 2 x 7200		2 x 15000	3000	*		FF / Oct'98

LO 1000 / hydr 400 / bl-gr 4000 / bilge 1000 / slu 500												
	B_{II} 5.65											
sludge 1 x 500												
LO 1000 / slu 1 x 2500 / oily bilge 300	Bh 5											
LO 500 / swe 3000 / slu 1000												
Other Capacities / Weights	Other											

167

			c 76 + 30 up						
			325 + 105 up						

pax distribution

37 VC-4d

Ship	pax & lug	cars & trucks/buses	crew & eff	fuel	water	lube	store	catering
BC1b	33.75	57.5	2	12	1.25		(&eng)5	
BC2b	56.25	35	1.25	25	0.5		(&eng)3	
BC3b	45 + 3	192.5 / 232.5	1.2	41	4	0.9	3.25	
BC10	59.55 + 11.9	237.5	2.75	40	10		3 (E/R)	8 (bar st.)
BC11	158	900 (cargo)	5	350	(&prov)15	5		
BC21b	45 + ?	220.5	2.4	49.8	4	0.51	3	
BC22a	28.08	37.5 / 52.5	1	7 / 15.3	1 / 2	0.5		(&store)2/3
BC23	52.5	35	1.5	25	2.5	(&eng)1		(&store)5.5
BC27	75	375	3	61	7			
BC28	28.08	37.5 / 52.5	1	7 / 15.3	1 / 2	0.5	2 / 3	
BC42b	36 + 3	60	1	35	2		5	
BC57	60	240	3	32	3	0.85	0.41	
BM7c	100	281	3 + 3	70	8		6 + 4	
BM7d	80 + 3	274	3	70	8		6 + 4	
BM8	112.5 + 15 / 52.5 +	468 / 187 + 840	2	70 + 3res	15		8 (prov)	12.5 / 6.5
BM9	52.5	162.5 (cargo)	2	300	(&prov)6	2		
BM13b	60 + 6	219	2.5	32	7	1	7 + 2	3.5
BM27b	120	540	3	120	7	3	(sundr.)3	3
BM31	41.25 + 2.5	180		45	4	1.5		4.5
BS7	(& cars) 143.9		2.38	(&lub)55	(&prov)14.5			
BS8	52.5	100	1.5	(&lub)105	(&prov)15			
BW2	45	155	3	30	5	(&eng)1		(&store)11
BW2b	52	190	3	41	5	(&eng)1		(&store)8
BW3	60	220	3	30	5	(&eng)1		(&store)11
BW4	60 + 16	281.25	3	40	10		3 (E/R)	7 (bar st.)
BW5	33.57 + 9	90	2.75	40	7.5		3 (E/R)	4 (bar st.)
BW10	60	220	3	45	5	(&eng)1		(&store)11
AC19b	32.25		1	12	1	0.2	1.5	
ASW6	31.5		0.5	7	1			

DWT-1a 38

BW / cargo	DWT							
	112							
	123							
	290.85 / 330.85							
	372.7							
	1433							
HO.17/sew2	327.38							
	77.08 / 102.38							
	123							
	531							
	77.08 / 102.38							
	142							
HO.34/BG.4	340							
	475							
	448							
	706 / 1185							
	525							
	340							
	805							
	278.75							
36.08	251.86							
40	314							
	310							
	300							
	330							
	409							
	190							
	345							
	47.95							
margin 1	41	LS:	mach. 35	elec. 15	outf. 30	struc. 76	marg. 3	TOT. 159

DWT-1b 29

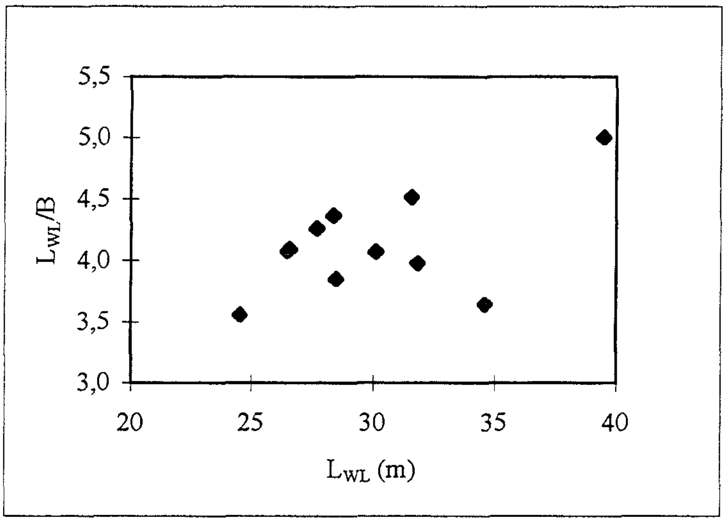
APPENDIX B: ADDITIONAL DATA PLOTS

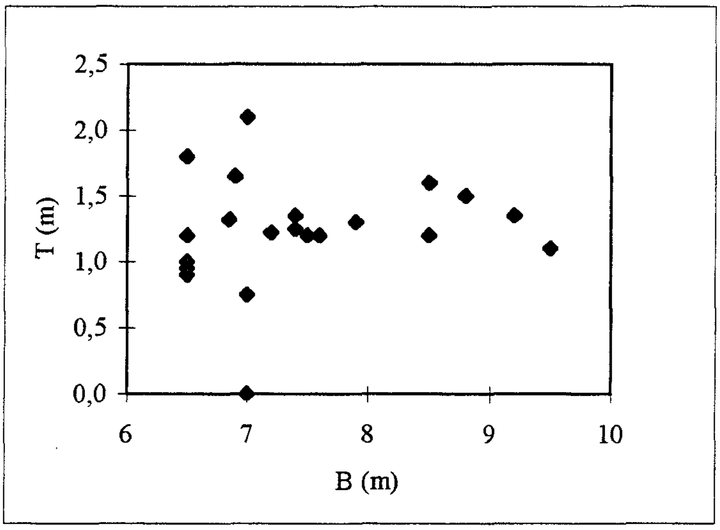
This appendix includes data plots which have not been used in the development of the algorithm for the calculation of main dimensions. These can be divided into two main categories. The first includes plots which showed satisfactory correlation and could have been used but were made redundant by the selected flowpath of the developed algorithm. The second category includes plots which are unusable due to the poor correlations between the two parameters. These include mostly plots of hull parameters against Froude number and are included here in order to demonstrate the validity of the decision not to include Froude number (speed) as a parameter for the derivation of main dimensions, which might at first seem strange if not properly justified.

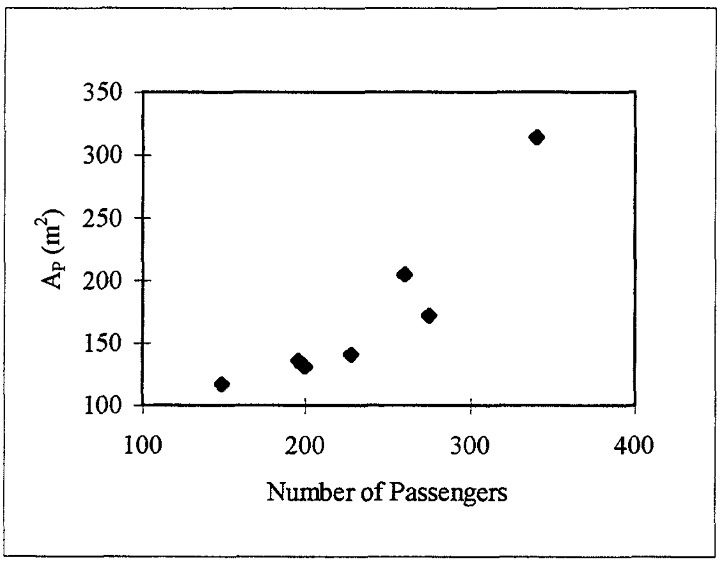
For the graphs that fall under the first category, the scatter is not significant and the satisfactory correlation means that they could be used if desirable. However the finalised algorithm is such that does not involve any steps that can be represented by these graphs. A characteristic example is that of the graphs of total passenger area and length-beam product against number of passengers. These show satisfactory correlations and could have been used in order to simplify the algorithm by allowing a more direct calculation of length-beam product, see Section 5.3. However it was preferred to adopt the three-step process for the calculation of the product, as is discussed in detail in Section 5.3, which allows greater flexibility in choosing the desirable level of accommodation quality and enhances the scope of the systematic generation of alternative designs.

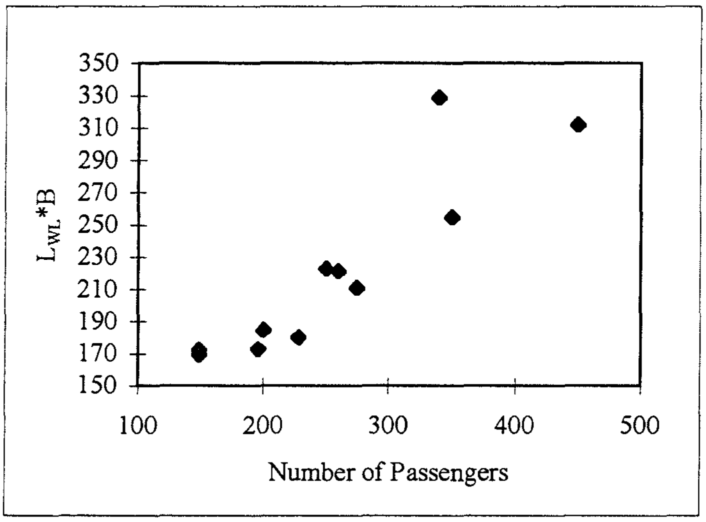
The graphs of the second category are interesting to observe as they show poor correlations in parameter combinations which could usually be expected to show clear trends. These are mostly hull parameters and ratios and it is interesting to see the poor correlations between such ratios and Froude number. These are often expected to follow specific trends but it can be seen that for the fast ferries in the database there is a complete scatter (no correlation at all) and in some cases even some trends which, although not clear, seem to be opposite to those normally expected.

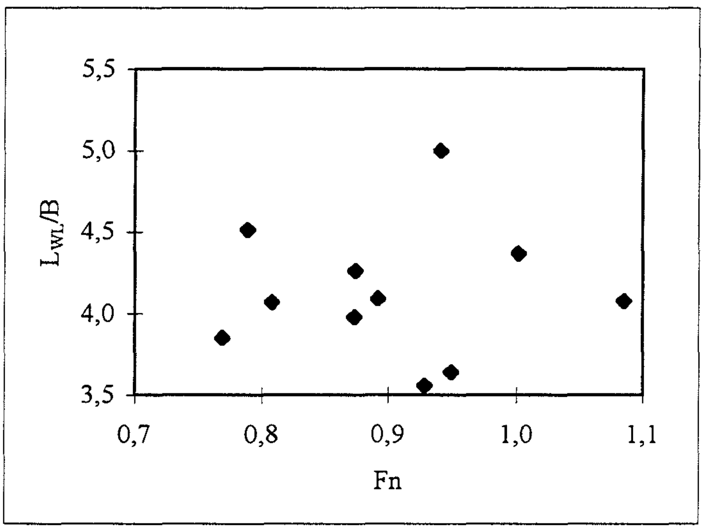
The plots are separated into the four main vessel categories, namely passenger-only monohulls, passenger-only catamarans, vehicle/passenger monohulls and vehicle/passenger catamarans.

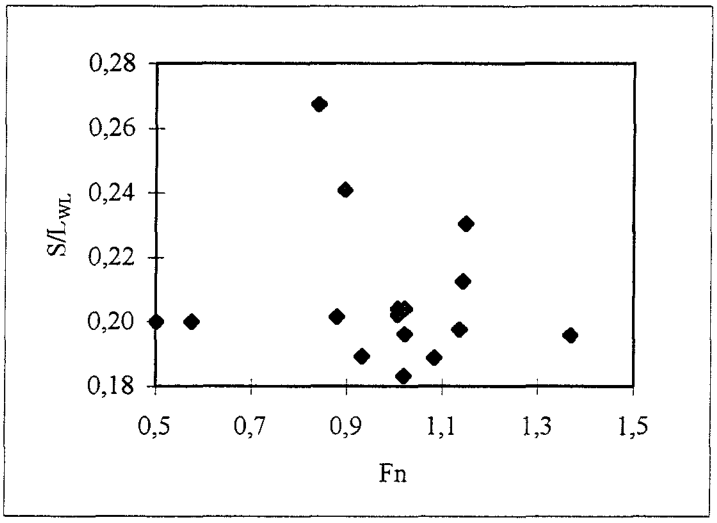

5,5
5,0
4,5
4,0
3,5
3,0
L_WL/B
20
25
30
35
40
L_WL (m)

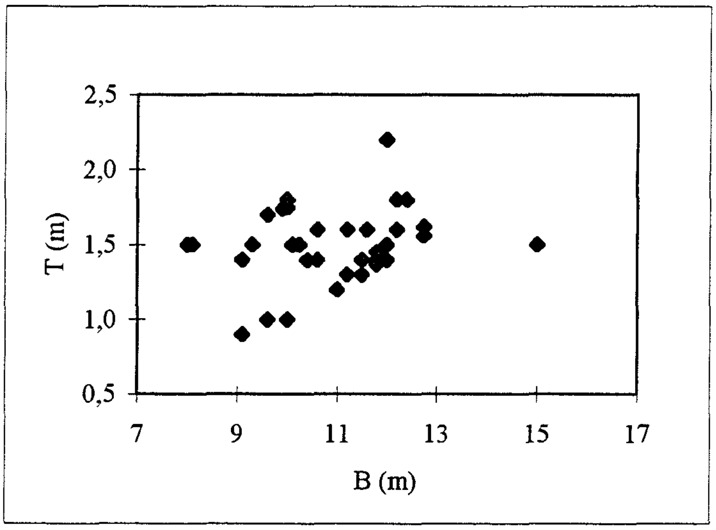

2,5
2,0
1,5
1,0
0,5
0,0
T (m)
6
7
8
9
10
B (m)

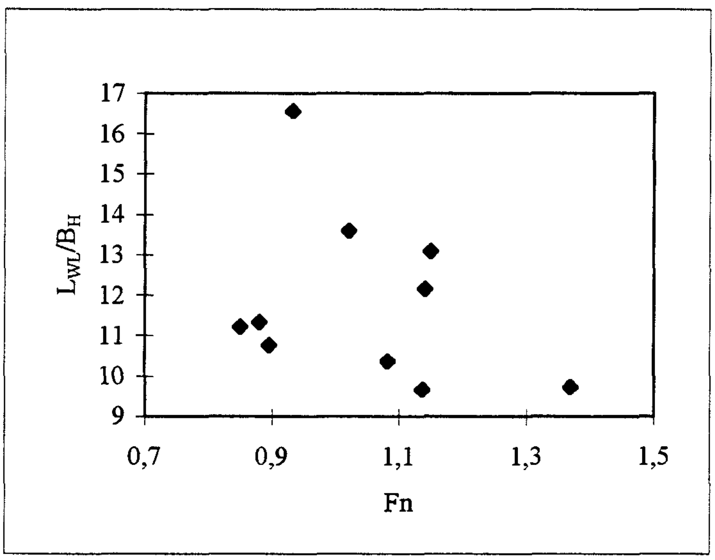

350
300
250
200
150
100
A_P (m^2)
100
200
300
400
Number of Passengers

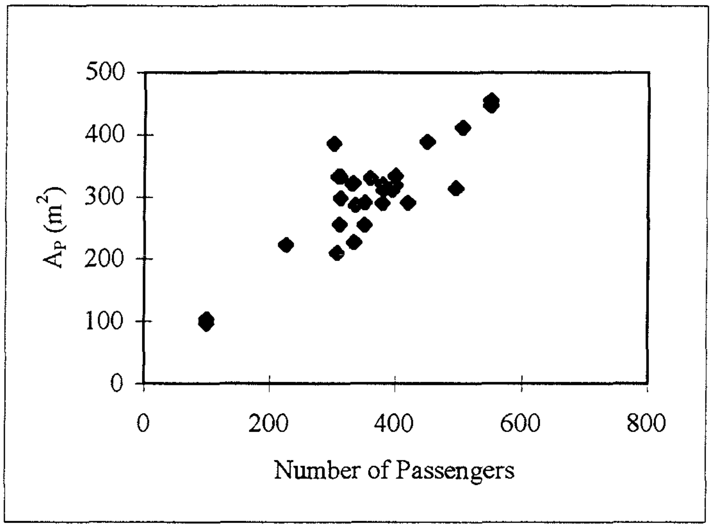

350
330
310
290
270
250
230
210
190
170
150
LWL*B
100
200
300
400
500
Number of Passengers

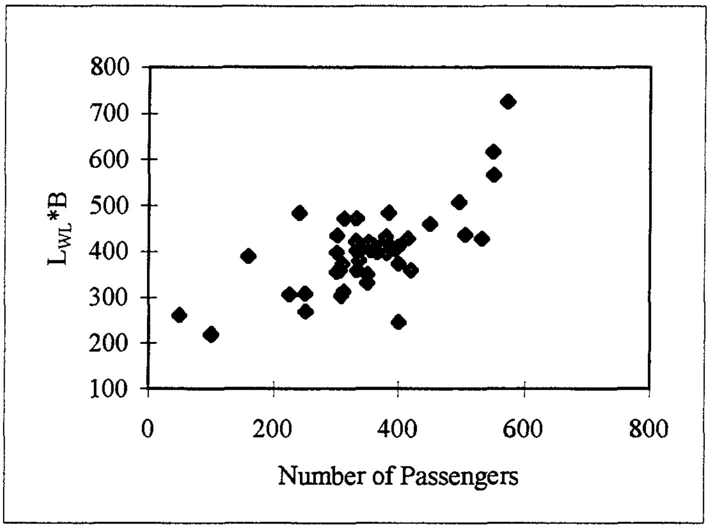

5,5
5,0
4,5
4,0
3,5
LWL/B
0,7
0,8
0,9
1,0
1,1
Fn

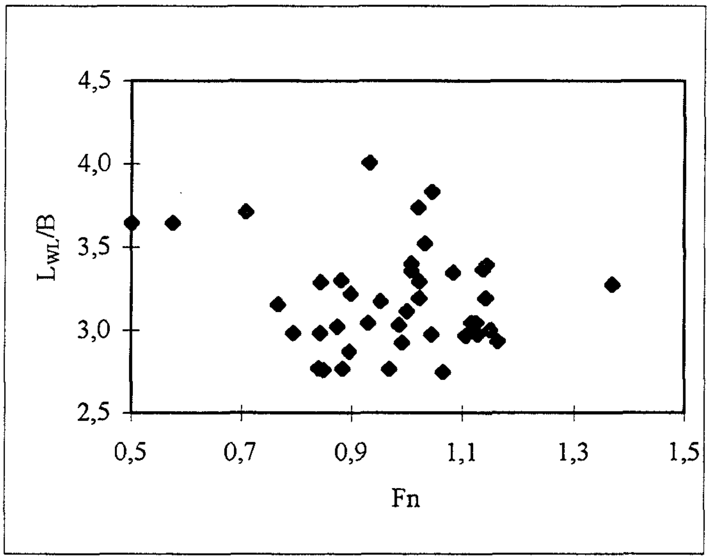

0,28
0,26
0,24
0,22
0,20
0,18
S/L_WL
0,5
0,7
0,9
1,1
1,3
1,5
Fn

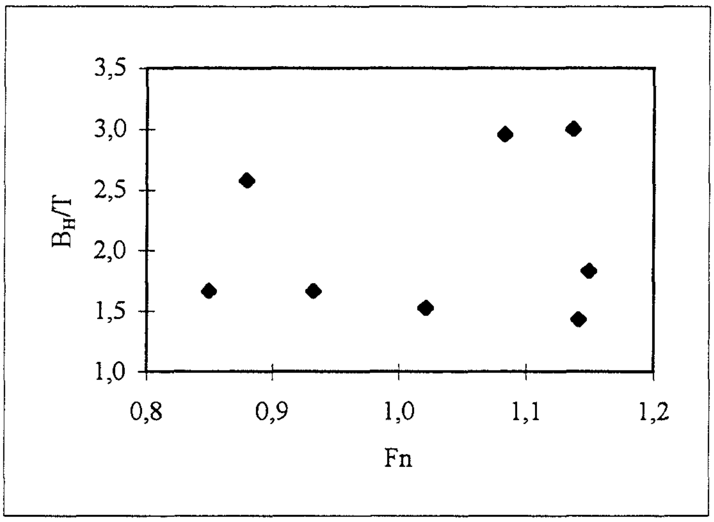

2,5
2,0
1,5
1,0
0,5
T (m)
7
9
11
13
15
17
B (m)

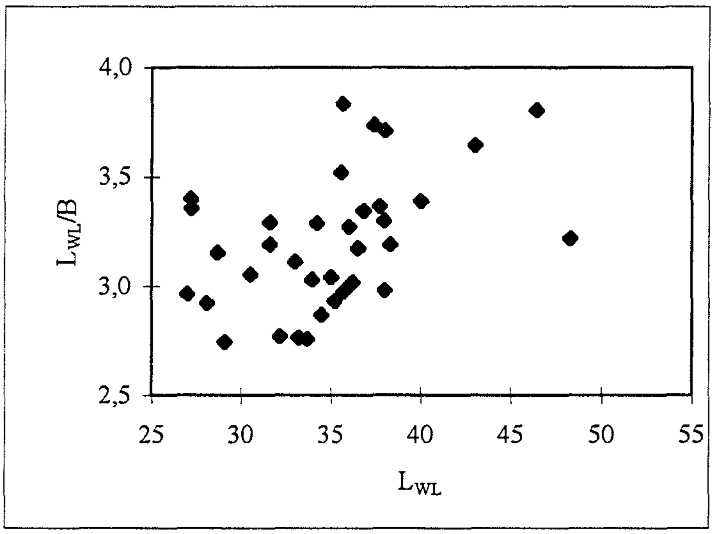

17
16
15
14
13
12
11
10
9
L_WL/B_H
0,7
0,9
1,1
1,3
1,5
Fn

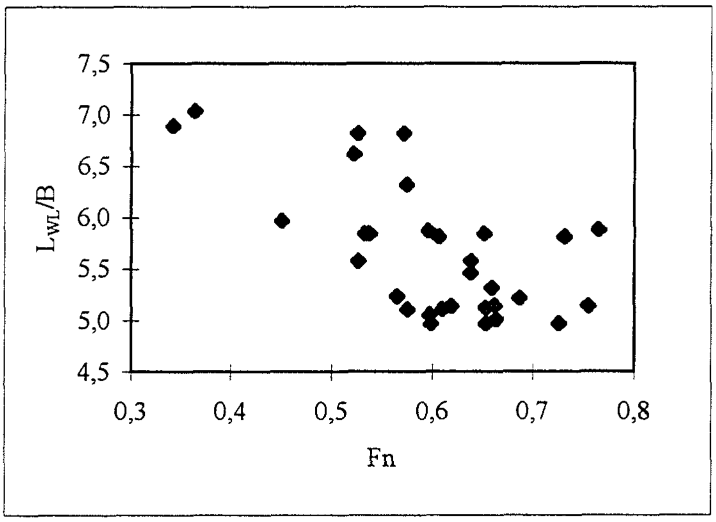

500
400
300
200
100
0
A_P (m^2)
0
200
400
600
800
Number of Passengers

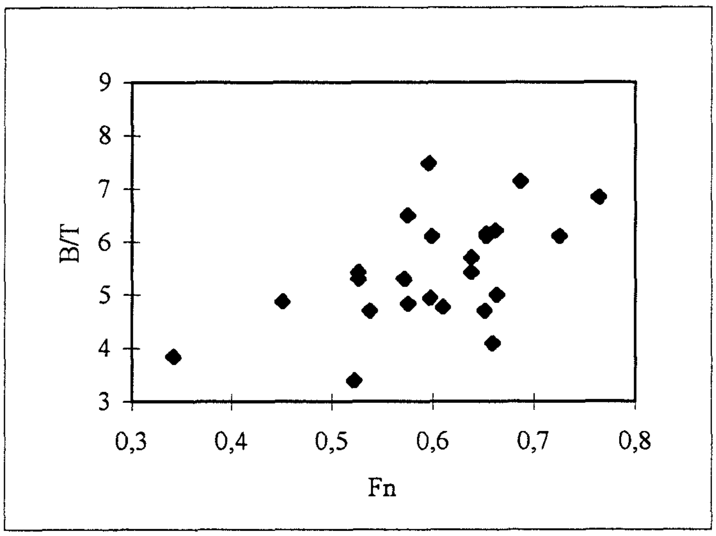

800
700
600
500
400
300
200
100
L_{WL}*B
0
200
400
600
800
Number of Passengers

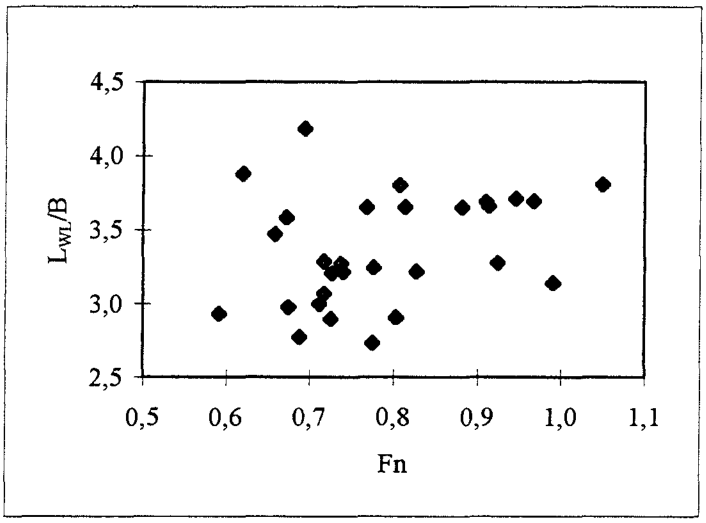

4,5
4,0
3,5
3,0
2,5
L_{WL}/B
0,5
0,7
0,9
1,1
1,3
1,5
Fn

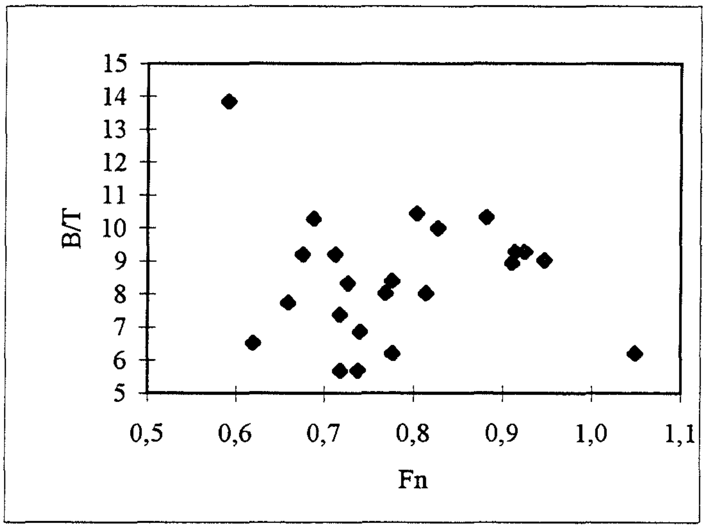

3,5
3,0
2,5
2,0
1,5
1,0
B_H/T
0,8
0,9
1,0
1,1
1,2
Fn

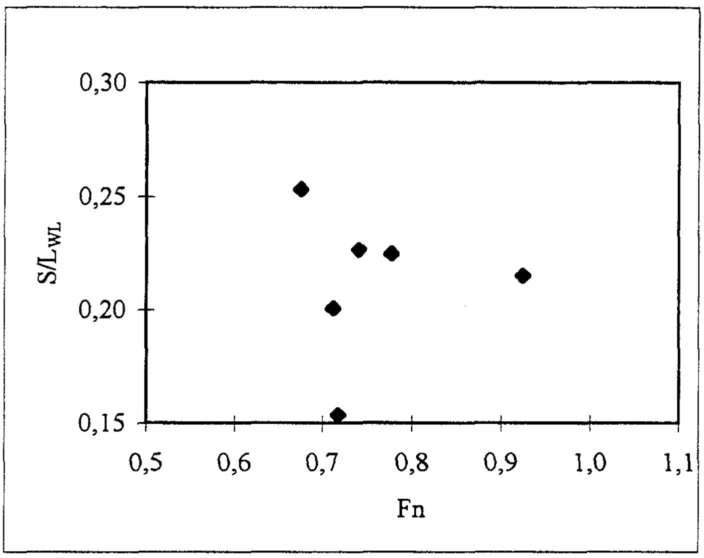

4,0
3,5
3,0
2,5
L_WL/B
25
30
35
40
45
50
55
L_WL

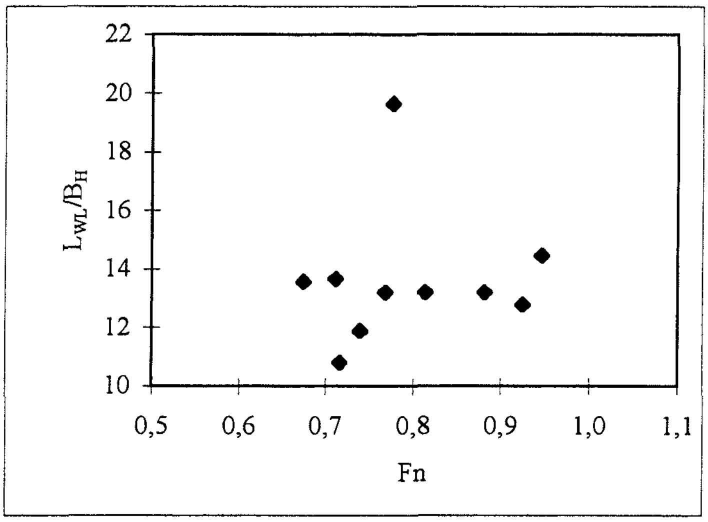

7,5
7,0
6,5
6,0
5,5
5,0
4,5
L_{WL}/B
0,3
0,4
0,5
0,6
0,7
0,8
Fn

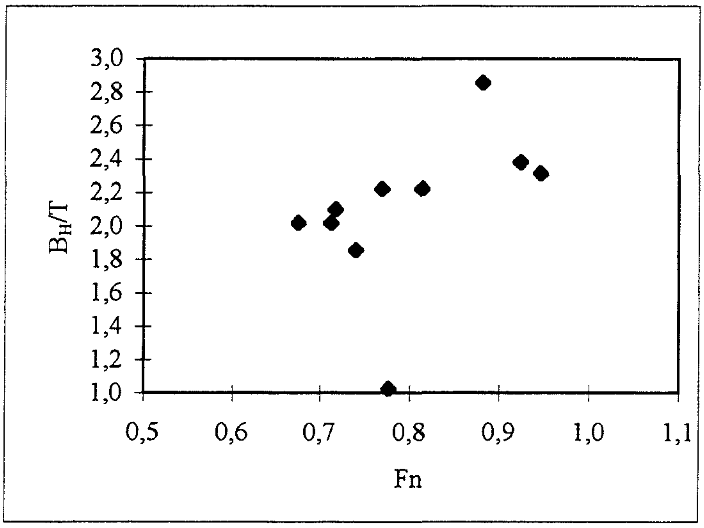

9
8
7
6
5
4
3
B/T
0,3
0,4
0,5
0,6
0,7
0,8
Fn


4,5
4,0
3,5
3,0
2,5
L_{WL}/B
0,5
0,6
0,7
0,8
0,9
1,0
1,1
Fn


15
14
13
12
11
10
9
8
7
6
5
B/T
0,5
0,6
0,7
0,8
0,9
1,0
1,1
Fn


0,30
0,25
0,20
0,15
S/L_{WL}
0,5
0,6
0,7
0,8
0,9
1,0
1,1
Fn


22
20
18
16
14
12
10
L_{WL}/B_H
0,5
0,6
0,7
0,8
0,9
1,0
1,1
Fn


3,0
2,8
2,6
2,4
2,2
2,0
1,8
1,6
1,4
1,2
1,0
B_H/T
0,5
0,6
0,7
0,8
0,9
1,0
1,1
Fn

APPENDIX C: SUMMARY OF FUZZY SET THEORY

A brief summary of some major issues relating to the use of fuzzy sets is given in this appendix. The use of fuzzy sets is important for the developed model as it offers a number of advantages of relevance to the needs of the model. The main purpose of the brief summary given here is to demonstrate these advantages in view of the developed research programme rather than to offer a comprehensive theoretical background to the mathematical theory.

The development of the concept of fuzzy sets and the related theory originated from the realisation that conventional mathematics involving crisp sets fail to model many real life problems realistically. This is particularly the case with problems of humanistic nature and in general problems where natural language terms are involved. These contain an inherent uncertainty and lack of accuracy in the definition of terms which cannot be modelled using crisp sets which are by nature specific and strict in their limits.

For example, let us consider the case where one wants to model the term, say, 'around 25°C'. Depending on the context or specific application and possibly on personal perception, it could be decided for example that the temperatures which satisfy this requirement are between, say, 23°C and 27°C. The crisp set [23,27] would then be used. It can be seen that in this case a temperature of 23.0°C would be considered to be 'around 25°C' whereas a temperature of 22.99°C would not, which does clearly not make much sense in a real life situation.

Another, even more illustrative, case is where one wants to model terms such as 'high' or 'low', 'good' or 'bad' and so on, in other words terms which represent qualitative characteristics, described in natural language usually by adjectives. If one tries to model for example the term 'a cheap ship', then depending again on the specific application, context, ship type and so on it could be decided that ships with an acquisition cost of less than, say, $30 million are cheap. Again it can be seen that, in such a model, a ship of $29,999,999 would be considered cheap and a ship of $30,000,000 would be considered expensive.

An infinite variety of such examples can be defined and do exist in numerous applications in all scientific fields, from social sciences to engineering. This is the case with the current research programme as well. As can be seen in Section 7.2

and in Fig.7.2.2, in order to be considered 'satisfactory' a fast ferry must be 'cheap to buy and run', have 'good seakeeping characteristics', offer 'high accommodation quality' and be 'attractive' and 'reliable'. Following the brief examples discussed earlier it is clear that the use of crisp sets would create problems in the sense of failing to model these goals realistically.

The major limitation, and disadvantage for such problems, of crisp sets is that a number can either belong to such a set or not, without any intermediate conditions. This offers a 'black-or-white'-type representation of situations which is clearly not realistic in many cases. The concept of fuzzy sets is based exactly on eliminating this limitation: a number can fully belong or not belong to a fuzzy set but it can also belong to the set with any intermediate level between 100% and 0. This is possible through the definition and use of membership functions and membership grades.

Whereas a crisp set is simply defined by a range of numbers which belong to it, a fuzzy set is defined by range of pairs of numbers and their respective membership grade in the set. Membership grades are numbers between 0 and 1 indicating the level to which a number belongs to the fuzzy set. These could in theory be assigned to different numbers in some way, arbitrarily or in some other more sophisticated way. It is simpler, however, to define a membership function, i.e. a mathematical function which directly indicates the membership grades of all numbers within its range.

As the aim is to model subjective or natural language terms, the definition of a membership function is also subjective. Its shape, i.e. the shape of the graph representing membership grades against parameter values, depends on the user's perception of how different shapes represent the goal being modelled. This includes the selection of the limits which define the range of values that get a zero or positive membership grade (i.e. do not belong or belong to the set) or a membership grade of one if appropriate. Wider or narrower ranges of non-zero membership grades can be defined determining how strict a goal is or how important the respective attribute is considered to be. Slopes and curvatures within the range of parameter values with non-zero membership grades can also be selected to quantify similar considerations, generating functions which are stricter or more 'forgiving' according to the needs of the specific application and the wording of the relevant goals.

The figures given at the end of this appendix show possible membership functions for the two examples discussed earlier, i.e. 'temperature around 25°C' and 'a cheap ship'. In both these graphs sinusoidal and parabolic functions are shown; other shapes (function types) could have been applied as well if considered more appropriate according to the perception of the user. Starting, say, from an initial sinusoidal function (continuous line) it can be seen how the results change if for example a parabolic function is used instead within the same limits, or alternatively a sinusoidal function but with different limits (aspirations).

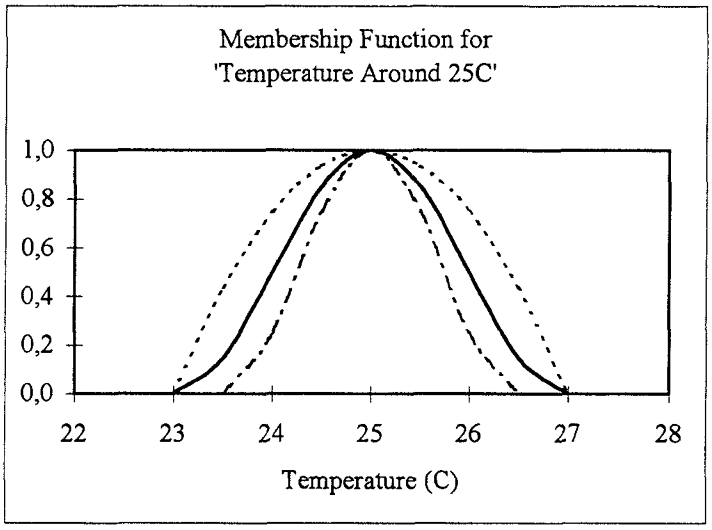
A major distinction can be made between two broad categories of membership functions, according to the type of the goals being modelled. The first concerns goals such as 'not much higher than...', 'significantly less than...', 'preferably larger than...', and in general those involving upper or lower limits. These functions have two infinite parts where the membership grade is respectively 0 and 1 and a part in the middle where the membership grades vary from 0 to 1 according to the selected shape. On the other hand there are functions which model goals such as 'around...', 'not too different than...' and in general those involving a central value. In such case the functions have infinite parts with zero membership functions at both ends and a central part with a peak (membership function of one) in the middle. In this case there may be only a single point or a narrow range of values with a membership function of one. These can be seen in the graphs at the end of the appendix.

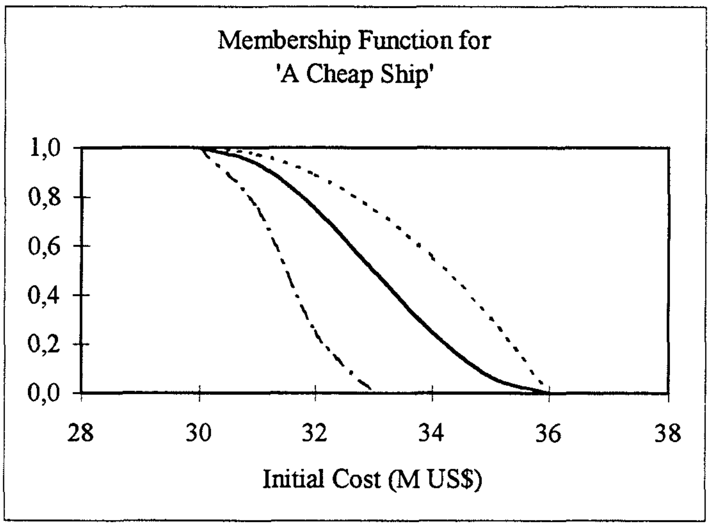
It can be seen that crisp sets are in a sense special cases of fuzzy sets. They can be considered as fuzzy sets with 'flat' (step) membership functions, i.e. with a membership grade of one everywhere within a range and a membership grade of zero anywhere outside that range.

Fuzzy sets can be used and offer advantages in a much wider range of applications than their name implies. There is of course the case of truly 'fuzzy' problems where qualitative terms such as 'attractive' or 'good' are involved. However, what is of greater interest for the needs of the current project is the possibility to model all types of goals and attributes with fuzzy sets. Even in cases of clearly defined and quantifiable parameters there may be uncertainties involved or lack of clarity in the definition and wording of the relevant goals. Fuzzy sets are perfectly suited for such problems and it is in this context that they prove to be useful for the developed model.

It can be seen that several of the selected primary attributes represent quantifiable -and, ultimately, clearly defined- technical or economic qualities, see Section 7.2. They are, however, of significantly varying nature; also, when the model is applied the goals may not be specifically defined. The use of fuzzy sets allows the uniform modelling and quantification of these different attributes and of the respective goals even if they involve vague language terms.

Fuzzy set theory is highly developed and sophisticated as a branch of modern mathematics. Detailed background as well as numerous applications can be found in existing literature, such as [78-80].





APPENDIX D: SUMMARY OF TAGUCHI'S METHOD

A brief summary of Taguchi's method is given in this appendix. This includes the basic terms and concepts relating to the method as well as brief comments on the application of the method in view of the developed research programme. The summary given here should extend the arguments in the main text of the thesis and help further indicate the merits of applying this method in the context of a concept design and decision making model such as the one presented in this thesis.

Taguchi's method is based on considerations related to the objectives of so-called quality engineering. According to Taguchi's own words, "it is the objective of quality engineering to choose from all possible designs the one that ensure the highest functional robustness of products at the lowest possible cost" where "a design is said to be 'functionally robust' if it inherently tends to diminish the effect of input variation on performance" [51].

Central to Taguchi's theory is the concept of quality loss. A successful design product is one that works satisfactorily throughout its life. Ideally, in this sense, every product should perform its intended function every time it is used, under all operating conditions during its expected lifetime without any harmful side effects. In this context the quality of a product is measured through the loss the user/ customer and the society in general suffers as a consequence of variations in the function of the product and related side effects; this loss equals zero if the quality is ideal [53].

A quality loss function is therefore introduced in robust design theory. When a functional characteristic y deviates from a specified target value m, the quality loss suffered is expressed as $L(y) = k(y-m)^2$ where k is a constant. If now one takes n representative measurements $y_1, y_2, \ldots, y_n$ of the quality characteristic y through the life cycle of the product, then the average quality loss caused by this product will be $Q = k[(\mu-m)^2 + ((n-1)/n)\sigma^2]$ or, when n is large, $Q = k[(\mu-m)^2 + \sigma^2]$ where μ and σ represent the mean value and variance of the measurements. It can be seen that the average quality loss depends on two distinct terms, one representing the average deviation of the quality characteristic from its target value and one representing the variance (scatter) of the quality characteristic relative to its observed mean value.

It is considered that it is easier to deal with the first term, i.e. develop products whose performance is on average very close to the desired target. It is more difficult and expensive to reduce the variance of a product's performance. This leads to the development of robust design theory. The aim is to reduce the variability of the performance of a product by selecting appropriate parameter values. This is possible by identifying the influences of the different design parameters on the mean and the variance which allows the selection and adjustment of the most suitable parameters and their values.

Taguchi's method offers the facility to perform such investigations in a way that significantly reduces the size of the problem. This is possible by performing appropriately designed 'experiments' where only a small number of parameter value combinations are examined. Orthogonal arrays (OAs) make this possible due to the inherent mutual orthogonality between any two columns (each column represents one parameter). This allows the investigation of the separate effects of each parameter, or control factor, as is desirable and the consequent identification of the most suitable values, without the need to investigate all possible combinations.

The number of combinations that need to be examined and in turn the size of the orthogonal array is defined by the concept of degrees of freedom. The degrees of freedom of an array must be at least equal to the degrees of freedom of the experiment. The former is one less than the number of combinations included in the array, i.e. one less than the number of rows (it can therefore be seen that the number of rows of the array must be at least one more than the required degrees of freedom). The latter is calculated through the number of parameters (factors) and the number of their different levels (values). The degrees of freedom needed to describe the effect of a factor is one less than the number of levels the factor takes and the total degrees of freedom of the experiment is the product of the number of factors and the degrees of freedom of each factor. This leads to the development of standardised orthogonal arrays. For example the L27 has, as its name suggests, 27 rows and therefore 26 degrees of freedom. It is therefore suitable for investigating experiments with up to 13 factors at 3 levels each, in which case the required degrees of freedom is $13x(3-1)=26$. Standardised OAs can be found in Appendix E and in [54-55].

Similarly, orthogonal arrays are used for the tabulation of combinations of noise factors. These are the external parameters which cause the undesirable variations in the performance of a design or product and generate the need for robust designs. These are treated in the same way as control factors (design parameters) in terms of degrees of freedom and orthogonal arrays. In this way, a number of alternative scenarios are generated through different combinations of noise factor values exactly as alternative designs are generated through different combinations of control factor values. This allows the development of an integrated methodology where numerous designs are simultaneously tested in numerous scenarios.

Once an experiment has been set up and investigated, the final selection of the most robust design is performed through the use of an appropriate signal-to-noise ratio. This ratio takes into account both the mean and the variance of the results allowing the selection to be performed according to the objectives of quality engineering. The design with the highest S/N ratio is selected as it is the one the minimises the effects of variations of uncontrollable external factors and at the same time demonstrates good average performance; in other words it is the most robust design.

The definition of S/N ratios is based on the considerations discussed earlier concerning the quality loss function, as in essence the most robust design should be the one that minimises quality loss. Limitless varieties of signal-to-noise ratios can be defined in principle according to the needs of specific problems and the nature of the relevant quality functions. The three most commonly used S/N ratios are: 'larger is better', see Eq. (8.3.1); 'smaller is better', whose definition is similar to the previous one with the $(1/y_i^2)$ replaced by y_i^2; and 'nominal is best' which is defined as $\eta = 10\log(\mu^2/\sigma^2)$. The names of these three S/N ratio types explicitly indicate the nature of the problems for which they are suitable.

This appendix offers a brief summary of the basic theory behind Taguchi's method. For a more comprehensive study of Taguchi's theory, and robust design and quality engineering in general, there is extensive literature on the subject, e.g. [51-54]. Indicative applications of the broad methodology in the marine field can be found in [47-49].

APPENDIX E: ORTHOGONAL ARRAYS

Orthogonal arrays form an integral part of the methodology and application of Taguchi's method, see Appendix D. This has been discussed in detail in the relevant appendix and in the main text of the thesis. Here some of the most useful arrays are included for reference. The selection given here includes the arrays which have been used during the development of the presented methodology and in the example application in Section 8.4, as well as a few other arrays that could be useful for similar investigations.

The most commonly used standard two- and three-level arrays are included. These are suitable and adequate for most applications and can be used for both control and noise factors. Special mention must be made about two of these arrays, namely the L12 (2^{11} - eleven factors at two levels) and the L18 (2^1x3^7 - one factor at two levels and seven factors at three levels). These are specially designed arrays which are particularly suitable for engineering-type problems and for this reason they are sometimes called 'engineering arrays'.

Additional arrays are included for reference even though they are not used in this thesis. These include arrays which can cope with more levels, e.g. four or five levels for each factor. This makes them useful for applications where it is desirable to investigate wider variations of factor level combinations, to the expense of the number of factors which inevitably has to be reduced in order to keep the size of the array constant. There are arrays which can cope with both many factors and many levels but they are particularly large. Many of the multi-level factors are modifications of standard two- or three-level arrays, where some of the columns (factors) are sacrificed to allow for the additional factor levels while keeping the degrees of freedom constant. A good example is that of the numerous modifications of the standard L16 (2^{15}) array; some of these modified arrays have as few as five columns but can cope with various combinations of up to four factor levels.

In this appendix, in addition to the arrays shown in full, a brief indicative list of a few other standard and customised arrays that can be found in literature is given, which indicates their scope (number of factors and levels). These, as well as numerous other OAs, can be found in [54-55].

TWO-LEVEL STANDARD ARRAYS

L8 (2^7)

↓run factor→	1	2	3	4	5	6	7
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

L12 (2^{11})

	1	2	3	4	5	6	7	8	9	10	11
1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	2	2	2	2	2	2
3	1	1	2	2	2	1	1	1	2	2	2
4	1	2	1	2	2	1	2	2	1	1	2
5	1	2	2	1	2	2	1	2	1	2	1
6	1	2	2	2	1	2	2	1	2	1	1
7	2	1	2	2	1	1	2	2	1	2	1
8	2	1	2	1	2	2	2	1	1	1	2
9	2	1	1	2	2	2	1	2	2	1	1
10	2	2	2	1	1	1	1	2	2	1	2
11	2	2	1	2	1	2	1	1	1	2	2
12	2	2	1	1	2	1	2	1	2	2	1

L16 (2^{15})

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
3	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
4	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
5	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2
6	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1
7	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1
8	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2
9	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
10	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1
11	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1
12	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2
13	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1
14	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2
15	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2
16	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1

THREE-LEVEL ARRAYS

L9 (3^4)

↓run factor→	1	2	3	4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

L18 (2^1x3^7)

	1	2	3	4	5	6	7	8
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

THREE-LEVEL ARRAYS (cont'd)

L27 (3^{13})

	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

L32 (2^1x4^9)

	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3	3	3
4	1	1	4	4	4	4	4	4	4	4
5	1	2	1	1	2	2	3	3	4	4
6	1	2	2	2	1	1	4	4	3	3
7	1	2	3	3	4	4	1	1	2	2
8	1	2	4	4	3	3	2	2	1	1
9	1	3	1	2	3	4	1	2	3	4
10	1	3	2	1	4	3	2	1	4	3
11	1	3	3	4	1	2	3	4	1	2
12	1	3	4	3	2	1	4	3	2	1
13	1	4	1	2	4	3	3	4	2	1
14	1	4	2	1	3	4	4	3	1	2
15	1	4	3	4	2	1	1	2	4	3
16	1	4	4	3	1	2	2	1	3	4
17	2	1	1	4	1	4	2	3	2	3
18	2	1	2	3	2	3	1	4	1	4
19	2	1	3	2	3	2	4	1	4	1
20	2	1	4	1	4	1	3	2	3	2
21	2	2	1	4	2	3	4	1	3	2
22	2	2	2	3	1	4	3	2	4	1
23	2	2	3	2	4	1	2	3	1	4
24	2	2	4	1	3	2	1	4	2	3
25	2	3	1	3	3	1	2	4	4	2
26	2	3	2	4	4	2	1	3	3	1
27	2	3	3	1	1	3	4	2	2	4
28	2	3	4	2	2	4	3	1	1	3
29	2	4	1	3	4	2	4	2	1	3
30	2	4	2	4	3	1	3	1	2	4
31	2	4	3	1	2	4	2	4	3	1
32	2	4	4	2	1	3	1	3	4	2

CUSTOM/MODIFIED ARRAYS (cont'd)

L25 (5^6)

	1	2	3	4	5	6
1	1	1	1	1	1	1
2	1	2	2	2	2	2
3	1	3	3	3	3	3
4	1	4	4	4	4	4
5	1	5	5	5	5	5
6	2	1	2	3	4	5
7	2	2	3	4	5	1
8	2	3	4	5	1	2
9	2	4	5	1	2	3
10	2	5	1	2	3	4
11	3	1	3	5	2	4
12	3	2	4	1	3	5
13	3	3	5	2	4	1
14	3	4	1	3	5	2
15	3	5	2	4	1	3
16	4	1	4	2	5	3
17	4	2	5	3	1	4
18	4	3	1	4	2	5
19	4	4	2	5	3	1
20	4	5	3	1	4	2
21	5	1	5	4	3	2
22	5	2	1	5	4	3
23	5	3	2	1	5	4
24	5	4	3	2	1	5
25	5	5	4	3	2	1

CUSTOM/MODIFIED ARRAYS (cont'd)

L8 (4^1x2^4)

	1	2	3	4	5
1	1	1	1	1	1
2	1	2	2	2	2
3	2	1	1	2	2
4	2	2	2	1	1
5	3	1	2	1	2
6	3	2	1	2	1
7	4	1	2	2	1
8	4	2	1	1	2

L16 (4^5)

	1	2	3	4	5
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2

OTHER ARRAYS:

L4 (2^3)
L32 (2^{31})
L64 (2^{63})
L54 (2^1x3^{25})
L81 (3^{40})
L64 (4^{21})
L50 (2^1x5^{11})

L36 ($2^{11}x3^{12}$)
L36 (2^3x3^{13})
L16 (4^1x2^{12})
L16 (4^2x2^9)
L16 (4^3x2^6)
L16 (4^4x2^3)

* Note that the numbers in the brackets indicate the number of 'runs' necessary in order to examine all the possible factor level combinations in a full factorial investigation and therefore demonstrate the significant reductions in problem size achievable through the use of orthogonal arrays.

APPENDIX F: COMPUTER PROGRAMS AND SPREADSHEETS

This appendix includes some basic information on the computer programs and spreadsheets which have been developed as part of the research programme. These largely constitute the modules of the technical design framework but also include programs and spreadsheets concerning costing calculations as well as calculations performed within the decision making framework. Full listings of source codes are also included.

Main Spreadsheet

A large spreadsheet called 'TAGUCHI' has been programmed in Excel to allow initial semi-automated application of the decision making method. The facilities included in the spreadsheet include the systematic generation of designs and scenarios, calculation of main dimensions, fuzzification including calculation of membership grades and overall ranking indices, and sensitivity analysis. It can therefore be seen that the spreadsheet allows a mechanised application of several steps of the methodology. Powering and seakeeping calculations as well as mass and costing estimates at present still need to be performed separately using various computer programs as outlined in this appendix.

The spreadsheet first allows the overall problem to be set up according to the outline in Section 8.4. This involves the selection and creation of appropriate orthogonal arrays for the systematic generation of designs and scenarios. This spreadsheet includes the L27, L18 and L9 arrays for the generation of first- and second-cycle designs and the L18 and L9 arrays for the generation of scenarios. The three levels for each control or noise factor are the only necessary input, together with any parameters that will be kept constant in smaller-size problems, as in the illustrative example application in Section 8.4 for example. The OAs are then generated automatically defining the alternative designs and scenarios. The design generation sheets also perform the calculation of main dimensions for each design according to the algorithms in Figs. 5.3.1 and 5.3.2. All the calculations in this spreadsheet are performed separately for monohulls and catamarans.

After all the designs and scenarios have been generated, the primary goals are fuzzified. Appropriate membership functions, defined by the user, are used as an input. According to these the seven primary attributes for each design in each scenario are normalised in the form of membership grades. The ranking index in each case is then calculated directly as the average of the seven membership grades; the spreadsheet offers the facility to use the minimum criterion instead if preferable. It is apparent that before this fuzzification is performed the necessary performance characteristics must first be defined, i.e. the separate programs performing technical and costing calculations must be run independently.

The calculated ranking indices are used as input for the final part of the spreadsheet which performs the sensitivity analysis. This can be performed for 9 or 18 scenarios, depending on which OA has been used for scenario generation, and for up to 27 alternative designs. The mean value, variance and S/N ratio are calculated for each design. The final selection can then be performed as described in Section 8.4.

Powering Calculations

Two programs have been written for performing powering calculations, one for monohulls and one for catamarans, named 'MONPOWER' and 'CATPOWER' respectively. These are used for calm-water resistance and propulsion calculations as described in Section 5.4.

Calm-water resistance calculations are performed using the systematic series data outlined in Section 5.4.1 and in Appendix G. For monohulls these include the NPL, 64 and Southampton series. For catamarans the Southampton and 64 series are included, although the use of the latter is not recommended at present, see Appendix G. The calculations are straightforward; C_R data files are read and all the necessary calculations are performed including any relevant interpolations.

Propulsion calculations are performed both for waterjets and conventional propellers. For waterjets an overall efficiency is calculated directly using the data in [110-111]. For propellers a standard η_0 optimisation procedure has been coded in the programs. Data files are also read in this case, containing the systematic data of the Wageningen-B [112] and the Gawn-Burrill series.

The user of the two programs needs to input the major parameters, e.g. vessel dimensions and speed, and secondary parameters when necessary, such as shaft and propeller characteristics necessary for propeller efficiency calculations. The calculations are then performed automatically both for waterjets and for propellers leading to the final output which is installed power and in the case of propellers optimum rotation speed.

Mass Estimates

In Section 5.5 the level of development and current limitations of the masses module have been discussed. These are reflected in the relevant computer program, called 'MASS'. This program is fully operational but some of the calculations in it are in need of revision as the relevant parts of the masses database are still under development.

The initial input to the program includes main dimensions, capacities and installed power. Hull mass is estimated using an initial form of a specialised equipment numeral for high-speed craft. This is currently under further development as part of ongoing work at the University of Southampton and when final results are available an update to the computer code will be possible. The regressions for main machinery mass calculations presented in Section 5.5 are coded into the program and allow direct calculations based on installed power. Total machinery mass is then calculated through a factor. The program also includes the calculation algorithms for outfit mass and deadweight as presented in the relevant section in the main text, allowing the complete calculation of a vessel's displacement.

Costing Estimates

Three programs have been written for performing initial costing estimates, called 'COST', 'COSTB' and 'COST98'. They are in chronological order and are gradually tuned to the needs of the decision making model. The first program allows full running cost calculations for any one vessel to be performed while the last focuses on fuel cost only, which is the finally selected relevant primary attribute, but allows the systematic investigation of alternative designs according to the structure of the decision making model. The second program lies between the two both chronologically and in its structure.

The most recently developed program 'COST98' includes the algorithms for detailed building cost calculations discussed in Section 6.2. These allow the calculation of hull, machinery and outfit costs based on hull mass, installed power, capacities and areas. As this detailed algorithm is under further development the computer code can respectively be updated. At the moment the overall building cost regressions (see Section 6.2) are used for an initial calibration of the algorithm and validation of the results. Fuel cost is calculated using installed power and fuel consumptions as well as operating profile parameters as input. Full listing is given only for the latest version, 'COST98'. It should be noted that, as the development of this program was based on the earlier versions, parts of the original codes that are not used anymore are kept as comment lines; in this way it can be seen, for example, how detailed running cost calculations can be (and were in initial versions) performed.

Additional Spreadsheets

Other spreadsheets have been developed in conjunction with the databases for hull mass, machinery mass and costing (overall and detailed) estimates. These have been used for the statistical analyses of the data and the development of the relevant algorithms. The results have led to the development of the relevant computer programs. The structure of these spreadsheets reflects their initial purpose and does not make them suitable for use in conjunction with the main overall spreadsheet for the practical application of the method. The use of the computer programs instead is more convenient, except for main dimensions.

Summary

The suite of computer programs and spreadsheets outlined here allows the full investigation and application of the developed method. A few of them may require further updating in the future but at the moment they are adequate for demonstrating the use of the overall method and they have been used to produce the calculations and results presented in the illustrative example application in Section 8.4.

All the programs and spreadsheets have been developed with the needs and aims of the overall model in mind. They are therefore easy to use and produce their results in such a way that they can be transparent and easily identifiable. As this is a model to be used for comparative studies of systematically generated designs and scenarios, the programs allow such studies to be investigated through simple iterative loops suitable for repeated parametric variations. All computer programs have been written in FORTRAN.

level	A_S/N_P	A_P/A_S	eng	S/L	$L/\nabla^{1/3}$	B_H/T	hull	prop		N_P		m	m	m	t	m	m
1	0,80	1,30	D	0,21	8,6	1,6	Al	P		620							
2	1,10	1,50	CD	0,23	9,0	2,0	AlSt	WJ		N_V							
3	1,40	1,70	GT	0,25	9,4	2,4	St	-		160							
										V_S							
design	(pax)									36	kn	L	B_H	T	Δ	S	B
1	0,80	1,30	D	0,21	8,6	1,6	Al	P				50,05	3,97	2,48	404	10,51	14,48
2	0,80	1,50	CD	0,23	9,0	2,0	AlSt	P				51,04	4,23	2,11	374	11,74	15,97
3	0,80	1,70	GT	0,25	9,4	2,4	St	P				51,99	4,42	1,84	347	13,00	17,41
4	1,10	1,30	D	0,23	9,0	2,4	St	P				54,28	4,92	2,05	450	12,48	17,41
5	1,10	1,50	CD	0,25	9,4	1,6	Al	P				57,85	4,01	2,51	478	14,46	18,48
6	1,10	1,70	GT	0,21	8,6	2,0	AlSt	P				63,20	5,60	2,80	814	13,27	18,88
7	1,40	1,30	CD	0,21	9,4	2,0	St	P				63,64	4,94	2,47	636	13,36	18,30
8	1,40	1,50	GT	0,23	8,6	2,4	Al	P				63,59	6,18	2,57	829	14,63	20,80
9	1,40	1,70	D	0,25	9,0	1,6	AlSt	P				67,60	5,01	3,13	869	16,90	21,91
10	0,80	1,30	GT	0,25	9,0	2,0	Al	WJ				46,67	3,86	1,93	286	11,67	15,53
11	0,80	1,50	D	0,21	9,4	2,4	AlSt	WJ				52,56	4,47	1,86	358	11,04	15,51
12	0,80	1,70	CD	0,23	8,6	1,6	St	WJ				54,10	4,29	2,68	510	12,44	16,73
13	1,10	1,30	CD	0,25	8,6	2,4	AlSt	WJ				52,17	5,07	2,11	458	13,04	18,11
14	1,10	1,50	GT	0,21	9,0	1,6	St	WJ				61,34	4,54	2,84	649	12,88	17,43
15	1,10	1,70	D	0,23	9,4	2,0	Al	WJ				62,28	4,83	2,42	596	14,32	19,16
16	1,40	1,30	GT	0,23	9,4	1,6	AlSt	WJ				62,37	4,33	2,71	599	14,35	18,67
17	1,40	1,50	D	0,25	8,6	2,0	St	WJ				62,50	5,54	2,77	787	15,62	21,17
18	1,40	1,70	CD	0,21	9,0	2,4	Al	WJ				70,17	6,37	2,65	972	14,74	21,10
design	(pax/cars)											L	B_H	T	Δ	S	B
1	0,80	1,30	D	0,21	8,6	1,6	Al	P				68,62	5,44	3,40	1041	14,41	19,85
2	0,80	1,50	CD	0,23	9,0	2,0	AlSt	P				67,28	5,57	2,79	857	15,48	21,05
3	0,80	1,70	GT	0,25	9,4	2,4	St	P				66,25	5,63	2,35	718	16,56	22,19
4	1,10	1,30	D	0,23	9,0	2,4	St	P				68,25	6,19	2,58	894	15,70	21,89
5	1,10	1,50	CD	0,25	9,4	1,6	Al	P				70,07	4,86	3,04	849	17,52	22,38
6	1,10	1,70	GT	0,21	8,6	2,0	AlSt	P				74,16	6,58	3,29	1314	15,57	22,15
7	1,40	1,30	CD	0,21	9,4	2,0	St	P				75,18	5,83	2,92	1049	15,79	21,62
8	1,40	1,50	GT	0,23	8,6	2,4	Al	P				72,52	7,04	2,93	1229	16,68	23,72
9	1,40	1,70	D	0,25	9,0	1,6	AlSt	P				74,83	5,54	3,46	1178	18,71	24,25
10	0,80	1,30	GT	0,25	9,0	2,0	Al	WJ				63,97	5,30	2,65	736	15,99	21,29
11	0,80	1,50	D	0,21	9,4	2,4	AlSt	WJ				69,29	5,89	2,45	821	14,55	20,44
12	0,80	1,70	CD	0,23	8,6	1,6	St	WJ				68,94	5,47	3,42	1056	15,86	21,32
13	1,10	1,30	CD	0,25	8,6	2,4	AlSt	WJ				65,60	6,37	2,65	910	16,40	22,77
14	1,10	1,50	GT	0,21	9,0	1,6	St	WJ				74,30	5,50	3,44	1153	15,60	21,11
15	1,10	1,70	D	0,23	9,4	2,0	Al	WJ				73,08	5,67	2,83	963	16,81	22,48
16	1,40	1,30	GT	0,23	9,4	1,6	AlSt	WJ				73,69	5,11	3,20	987	16,95	22,06
17	1,40	1,50	D	0,25	8,6	2,0	St	WJ				71,27	6,32	3,16	1167	17,82	24,14
18	1,40	1,70	CD	0,21	9,0	2,4	Al	WJ				77,69	7,05	2,94	1318	16,31	23,36

TAGUCHI.XLS

Generation of designs - L18 OA

(pax/cars designs valid in this example)

level	$H^{(1/3)}$	**f.p.**	**p.m.**	**T**				
1	2,1	130	15	5,9	7,1	8,1		
2	2,5	150	20	6,2	7,3	8,3		
3	2,9	200	25	6,5	7,5	8,5		
scenario								
1	2,1	130	15	5,9				
2	2,1	150	20	6,2				
3	2,1	200	25	6,5				
4	2,5	150	25	7,1				
5	2,5	200	15	7,3				
6	2,5	130	20	7,5				
7	2,9	200	20	8,1				
8	2,9	130	25	8,3				
9	2,9	150	15	8,5				

TAGUCHI.XLS

Generation of scenarios - L9 OA

level	$H^{(1/3)}$	i	N	BER	p.m.	f.p.	N_L	T
1	2,1	10	10	40	15	130	5	5,9
2	2,5	15	15	60	20	150	8	6,5
3	2,9	20	20	80	25	200	10	-
scenario								
1	2,1	10	10	40	15	130	5	5,9
2	2,1	15	15	60	20	150	8	5,9
3	2,1	20	20	80	25	200	10	5,9
4	2,5	10	10	60	20	200	10	7,1
5	2,5	15	15	80	25	130	5	7,1
6	2,5	20	20	40	15	150	8	7,1
7	2,9	10	15	40	25	150	10	8,1
8	2,9	15	20	60	15	200	5	8,1
9	2,9	20	10	80	20	130	8	8,1
10	2,1	10	20	80	20	150	5	6,5
11	2,1	15	10	40	25	200	8	6,5
12	2,1	20	15	60	15	130	10	6,5
13	2,5	10	15	80	15	200	8	7,5
14	2,5	15	20	40	20	130	10	7,5
15	2,5	20	10	60	25	150	5	7,5
16	2,9	10	20	60	25	130	8	8,5
17	2,9	15	10	80	15	150	10	8,5
18	2,9	20	15	40	20	200	5	8,5

TAGUCHI. XLS

Generation of scenarios - L18 OA

GOALS		satisfying	acceptable	
Building Cost	less than:	28	38	(M $US)
Annual Fuel Cost	less than:	3,5	n.a.	(M $US)
Total Passenger Area	at least:	1000	700	(m^2)
Motion Sickness Incidence	not much higher than:	10	20	(%)
Power Increase in Waves	less than:	10	20	(%)
Availability	at least:	85	70	(%)
Attractiveness	much better than:	n.a.	3	* 1=v.low, 2=low, 3=av., 4=high, 5=v.high
		(μ=1)	(μ=0)	

Scenario 1	Fuel price:		130	$/t	Power margin:			15	%	Wave height:		2,1	m	Wave period:	
design:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
B.C. (M$)	28,2	28,1	27,6	29,3	29,9	41,0	34,5	40,8	35,9	23,0	25,1	27,8	26,3	31,4	29,3
A.F.C. (M$)	2,90	2,71	2,53	2,87	2,55	4,01	3,17	3,95	3,19	1,81	1,88	2,32	2,14	2,55	2,07
P.A. (m^2)	645	744	843	887	1023	1159	1128	1302	1476	645	744	843	887	1023	1159
M.S.I. (%)	9,4	6,8	3,0	6,0	1,3	4,2	0,3	5,5	2,6	10,3	1,5	9,1	13,4	2,3	0,9
P.I. (%)	12,2	10,2	7,9	9,9	7,0	9,6	6,1	10,4	9,1	11,6	7,2	12,0	14,0	7,9	6,5
Av. (%)	87,6	91,2	96,1	92,2	98,1	93,6	99,5	92,0	95,8	87,6	97,9	88,0	83,4	86,5	99,1
A.I.	3,72	3,86	4,00	3,82	3,98	4,14	4,02	4,20	4,08	3,92	3,76	3,90	3,92	4,08	3,94

Scenario 2	Fuel price:		150	$/t	Power margin:			20	%	Wave height:		2,1	m	Wave period:	
design:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
B.C. (M$)	28,6	28,5	28,1	29,7	30,3	42,6	35,0	42,3	36,4	23,3	25,4	28,1	26,6	31,9	27,7
A.F.C. (M$)	3,75	3,13	2,92	3,31	2,94	4,63	3,67	4,56	3,68	2,09	2,17	2,68	2,47	2,94	2,38
P.A. (m^2)	645	744	843	887	1023	1159	1128	1302	1476	645	744	843	887	1023	1159
M.S.I. (%)	11,3	8,7	4,2	8,1	2,3	6,0	0,9	7,3	3,6	12,4	2,6	10,9	15,1	3,3	1,5
P.I. (%)	13,0	11,1	8,4	10,8	7,6	10,5	6,8	11,2	9,6	12,5	7,8	12,9	14,7	8,5	7,1
Av. (%)	85,0	88,7	94,5	89,5	96,8	91,0	98,7	89,4	94,4	85,1	96,5	85,4	81,1	90,1	98,1
A.I.	3,72	3,86	4,00	3,82	3,98	4,14	4,02	4,20	4,08	3,92	3,76	3,90	3,92	4,08	3,94

Scenario 3	Fuel price:		200	$/t	Power margin:			25	%	Wave height:		2,1	m	Wave period:	
design:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
B.C. (M$)	29,1	28,9	28,6	30,2	30,7	44,3	35,5	43,9	36,9	23,6	25,7	28,5	26,9	32,4	30,0
A.F.C. (M$)	4,47	4,17	3,89	4,42	3,92	6,17	4,87	6,08	4,91	2,79	2,89	3,57	3,70	3,92	3,18
P.A. (m^2)	645	744	843	887	1023	1159	1128	1302	1476	645	744	843	887	1023	1159
M.S.I. (%)	13,1	10,5	5,4	10,1	3,3	7,7	1,4	9,0	4,6	14,4	3,7	12,7	16,8	4,2	2,0
P.I. (%)	13,8	12,0	8,8	11,7	8,2	11,3	7,4	12,0	10,0	13,3	8,3	13,7	15,3	9,0	7,7
Av. (%)	82,4	86,1	92,9	86,7	95,5	88,3	97,9	86,7	93,0	82,5	95,0	82,8	78,8	93,6	97,1
A.I.	3,72	3,86	4,00	3,82	3,98	4,14	4,02	4,20	4,08	3,92	3,76	3,90	3,92	4,08	3,94

Scenario 4	Fuel price:		150	$/t	Power margin:			25	%	Wave height:		2,5	m	Wave period:	
design:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
B.C. (M$)	29,1	28,9	28,6	30,2	30,7	44,3	35,5	43,9	36,9	23,6	25,7	28,5	26,9	32,4	30,0
A.F.C. (M$)	3,75	3,13	2,92	3,31	2,94	4,63	3,67	4,56	3,68	2,09	2,17	2,68	2,47	2,94	2,38
P.A. (m^2)	645	744	843	887	1023	1159	1128	1302	1476	645	744	843	887	1023	1159
M.S.I. (%)	23,2	18,6	12,8	17,5	9,5	16,7	5,8	18,5	11,1	22,6	10,2	22,8	27,2	11,5	7,2
P.I. (%)	19,8	17,6	12,3	16,0	11,6	16,8	10,9	17,6	13,7	17,6	11,8	19,6	21,7	13,9	11,2

TAGUCHI.XLS Calculation of membership functions (grades) 1/3

5,9	s		Opp. rate:		10	%	Econ. life:		10	yrs				MEM
16	17	18	19	20	21	22	23	24	25	26	27		design:	1
30,4	31,1	36,3												1,000
2,23	2,48	2,91												1,000
1128	1302	1476												0,000
0,5	6,6	1,2												1,000
6,3	10,9	7,0												0,952
99,2	90,7	98,0												1,000
4,12	4,00	4,18												0,043
														OVE
														0,000
6,2	s		Opp. rate:		10	%	Econ. life:		10	yrs				MEM
16	17	18	19	20	21	22	23	24	25	26	27		design:	1
30,8	31,5	36,7												0,996
2,57	2,86	3,35												0,923
1128	1302	1476	0	0	0	0	0	0	0	0	0			0,000
1,2	8,5	1,4												0,984
7,0	11,8	7,4												0,910
98,3	88,0	97,3												1,000
4,12	4,00	4,18												0,043
														OVE
														0,000
6,5	s		Opp. rate:		10	%	Econ. life:		10	yrs				MEM
16	17	18	19	20	21	22	23	24	25	26	27		design:	1
31,2	31,9	37,2												0,988
3,43	3,82	4,47												0,215
1128	1302	1476	0	0	0	0	0	0	0	0	0			0,000
1,8	10,3	1,6												0,904
7,6	12,6	7,8												0,856
97,3	85,3	96,6												0,827
4,12	4,00	4,18												0,043
														OVE
														0,000
7,1	s		Opp. rate:		10	%	Econ. life:		10	yrs				MEM
16	17	18	19	20	21	22	23	24	25	26	27		design:	1
31,2	31,9	37,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0			0,988
2,57	2,86	3,35	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00			0,923
1128	1302	1476	0	0	0	0	0	0	0	0	0			0,000
6,8	20,0	8,8												0,000
11,2	18,2	12,8												0,040

TAGUCHI.XLS Calculation of membership grades 2/3

ERSHIP GRADES																
2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1,000	1,000	0,983	0,964	0,000	0,578	0,000	0,376	1,000	1,000	1,000	1,000	0,884	0,983	0,942	0,904	0,311
1,000	1,000	1,000	1,000	0,707	1,000	0,766	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,147	0,477	0,623	1,000	1,000	1,000	1,000	1,000	0,000	0,147	0,477	0,623	1,000	1,000	1,000	1,000	1,000
1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	0,999	1,000	1,000	0,884	1,000	1,000	1,000	1,000	1,000
1,000	1,000	1,000	1,000	1,000	1,000	0,998	1,000	0,974	1,000	0,960	0,840	1,000	1,000	1,000	0,992	1,000
1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	0,893	1,000	1,000	1,000	1,000	1,000
0,192	0,413	0,140	0,379	0,655	0,448	0,750	0,552	0,281	0,076	0,250	0,281	0,552	0,313	0,621	0,413	0,719
ALL GRAD	(ranking index)															
0,763	0,841	0,821	0,906	0,000	0,861	0,000	0,847	0,000	0,746	0,812	0,789	0,920	0,899	0,938	0,901	0,861
ERSHIP GRADES																
2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0,998	1,000	0,971	0,947	0,000	0,510	0,000	0,294	1,000	1,000	1,000	1,000	0,848	1,000	0,922	0,878	0,243
1,000	1,000	1,000	1,000	0,089	0,964	0,139	0,960	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,147	0,477	0,623	1,000	1,000	1,000	1,000	1,000	0,000	0,147	0,477	0,623	1,000	1,000	1,000	1,000	1,000
1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	0,945	1,000	0,992	0,740	1,000	1,000	1,000	1,000	1,000
0,988	1,000	0,994	1,000	0,998	1,000	0,986	1,000	0,940	1,000	0,919	0,784	1,000	1,000	1,000	0,969	1,000
1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	0,740	1,000	1,000	1,000	1,000	1,000
0,192	0,413	0,140	0,379	0,655	0,448	0,750	0,552	0,281	0,076	0,250	0,281	0,552	0,313	0,621	0,413	0,719
ALL GRAD	(ranking index)															
0,761	0,841	0,818	0,904	0,000	0,846	0,000	0,829	0,000	0,746	0,805	0,738	0,914	0,902	0,935	0,894	0,852
ERSHIP GRADES																
2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0,992	0,996	0,952	0,927	0,000	0,438	0,000	0,208	1,000	1,000	0,998	1,000	0,806	0,960	0,898	0,848	0,154
0,534	0,820	0,263	0,794	0,000	0,001	0,000	0,000	1,000	1,000	0,994	0,950	0,794	1,000	1,000	0,877	0,215
0,147	0,477	0,623	1,000	1,000	1,000	1,000	1,000	0,000	0,147	0,477	0,623	1,000	1,000	1,000	1,000	1,000
0,998	1,000	1,000	1,000	1,000	1,000	1,000	1,000	0,806	1,000	0,927	0,538	1,000	1,000	1,000	0,999	1,000
0,960	1,000	0,971	1,000	0,983	1,000	0,960	1,000	0,891	1,000	0,863	0,719	1,000	1,000	1,000	0,932	1,000
1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	0,833	1,000	0,853	0,587	1,000	1,000	1,000	1,000	1,000
0,192	0,413	0,140	0,379	0,655	0,448	0,750	0,552	0,281	0,076	0,250	0,281	0,552	0,313	0,621	0,413	0,719
ALL GRAD	(ranking index)															
0,689	0,815	0,707	0,871	0,000	0,698	0,000	0,000	0,000	0,746	0,766	0,671	0,879	0,896	0,931	0,867	0,727
ERSHIP GRADES																
2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0,992	0,996	0,952	0,927	0,000	0,438	0,000	0,208	1,000	1,000	0,998	1,000	0,806	0,960	0,898	0,848	0,154
1,000	1,000	1,000	1,000	0,089	0,964	0,139	0,960	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,147	0,477	0,623	1,000	1,000	1,000	1,000	1,000	0,000	0,147	0,477	0,623	1,000	1,000	1,000	1,000	1,000
0,260	0,922	0,438	1,000	0,551	1,000	0,278	0,988	0,000	1,000	0,000	0,000	0,978	1,000	1,000	0,000	1,000
0,422	0,947	0,640	0,974	0,538	0,992	0,422	0,863	0,422	0,968	0,078	0,000	0,848	0,986	0,986	0,328	0,922

TAGUCHI.XLS Calculation of membership grades 3/3

d/s	1	2	3	4	5	6	7	8	9		μ	σ	S/N
1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	0,000	#DIV/0!
2	0,763	0,761	0,689	0,486	0,425	0,496	0,000	0,000	0,000		0,402	0,324	#DIV/0!
3	0,841	0,841	0,815	0,802	0,783	0,814	0,633	0,694	0,725		0,772	0,072	-2,361
4	0,821	0,818	0,707	0,606	0,510	0,618	0,000	0,000	0,000		0,453	0,354	#DIV/0!
5	0,906	0,904	0,871	0,897	0,874	0,902	0,773	0,821	0,846		0,866	0,045	-1,283
6	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	0,000	#DIV/0!
7	0,861	0,846	0,698	0,834	0,717	0,851	0,672	0,815	0,839		0,793	0,074	-2,131
8	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	0,000	#DIV/0!
9	0,847	0,829	0,000	0,778	0,000	0,800	0,000	0,630	0,675		0,507	0,386	#DIV/0!
10	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	0,000	#DIV/0!
11	0,746	0,746	0,746	0,741	0,743	0,744	0,630	0,654	0,676		0,714	0,047	-2,979
12	0,812	0,805	0,766	0,000	0,000	0,000	0,000	0,000	0,000		0,265	0,397	#DIV/0!
13	0,789	0,738	0,671	0,000	0,000	0,000	0,000	0,000	0,000		0,244	0,368	#DIV/0!
14	0,920	0,914	0,879	0,860	0,843	0,868	0,644	0,699	0,740		0,818	0,099	-1,933
15	0,899	0,902	0,896	0,894	0,898	0,901	0,847	0,855	0,869		0,885	0,021	-1,071
16	0,938	0,935	0,931	0,929	0,936	0,934	0,884	0,893	0,911		0,921	0,020	-0,718
17	0,901	0,894	0,867	0,000	0,536	0,566	0,000	0,000	0,000		0,418	0,418	#DIV/0!
18	0,861	0,852	0,727	0,828	0,740	0,844	0,582	0,706	0,750		0,766	0,091	-2,511
19	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	0,000	#DIV/0!
20	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	0,000	#DIV/0!
21	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	0,000	#DIV/0!
22	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	0,000	#DIV/0!
23	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	0,000	#DIV/0!
24	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	0,000	#DIV/0!
25	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	0,000	#DIV/0!
26	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	0,000	#DIV/0!
27	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	0,000	#DIV/0!

TAGUCHI.XLS

Calculation of S/N ratios - 18 designs / 9 scenarios

```
      PROGRAM MONPOWER
      REAL LWL,LD,NI
      INTEGER Z
      CHARACTER *1 YN2,YN3,RESER
      COMMON/ONE/CR,FN,BONT,LD,CB
      COMMON/TWO/ALFA,FV
      COMMON/THREE/H0,DIAM,WT,BAR,Z,RTA,VS
      COMMON/FOUR/TD
      G=9.807
      NI=1.18831E-6
      CB=0.4
      HG=0.97
      HS=0.97
      OPEN (10,FILE='MON.OUT',STATUS='NEW')
      WRITE (*,*) ' '
      WRITE (*,*) '**************************************************'
      WRITE (*,*) ' '
      WRITE (*,*) ' PRELIMINARY ESTIMATION OF REQUIRED INSTALLED'
      WRITE (*,*) ' POWER FOR HIGH-SPEED MONOHULL FERRIES'
   14 WRITE (*,*) ' '
      WRITE (*,*) '**************************************************'
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT VESSEL''S MAIN DIMENSIONS IN THE FOLLOWING'
      WRITE (*,*) ' ORDER: LWL, B, T'
      READ (*,*) LWL,B,T
      BONT=B/T
      DVOL=LWL*B*T*CB
      D=DVOL*1.025
      LD=LWL/(DVOL**(1.0/3.0))
      WRITE (10,4001) D,LD
 4001 FORMAT (' DISP. = ',F6.1,' t',5X,'L/DISP = ',F5.2)
   13 WRITE (*,*) ' '
      WRITE (*,*) ' INPUT SPEED FOR WHICH TO PERFORM CALCULATIONS (KN)'
      READ (*,*) VSKN
      VS=VSKN*0.5145
      FN=VS/SQRT(G*LWL)
      RN=LWL*VS/NI
      WRITE (10,4002) VS,FN,RN
 4002 FORMAT (' VS = ',F5.2,' m/s',5X,'FN = ',F5.3,5X,'RN = ',E11.4)
   56 WRITE (*,*) ' '
      WRITE (*,*) ' SELECT SERIES TO BE USED FOR RESISTANCE CALCULATION'
      WRITE (*,*) ' (N)PL, (S)ERIES-64 OR (E)XTENDED NPL/SOUTHAMPTON'
      READ (*,55) RESER
      IF ((RESER.EQ.'N').OR.(RESER.EQ.'n')) THEN
      CALL CRCALCNP
        ELSE IF ((RESER.EQ.'S').OR.(RESER.EQ.'s')) THEN
        CALL CRCALC64
          ELSE IF ((RESER.EQ.'E').OR.(RESER.EQ.'e')) THEN
          CALL CRCALCSO
            ELSE
            WRITE (*,*) ' I SPECIFICALLY ASKED FOR AN N ,AN S OR AN E'
            GOTO 56
      ENDIF
      CF=(0.075/((ALOG10(RN)-2.0)**2.0))
      CT=CF+CR
      WRITE (*,24) CR,CF,CT
      WRITE (10,24) CR,CF,CT
   24 FORMAT (' CR = ',E14.4,5X,'CF = ',E14.4,5X,'CT = ',E14.4)
      IF ((RESER.EQ.'S').OR.(RESER.EQ.'s')) THEN
      CS=6.554423597-1.225559486*BONT+0.2161030028*(BONT**2.0)
     +  -15.40884518*CB+4.4468108569*BONT*CB-0.6940997418*(BONT**2.0)*CB
     +  +15.40377259*(CB**2.0)-4.527288815*BONT*(CB**2.0)
     +  +0.6552098659*((BONT*CB)**2.0)
        ELSE
        CS=2.5380616+0.049355*BONT+0.013070129*(BONT**2.0)
      ENDIF
      WS=CS*SQRT(LWL*DVOL)
      WRITE (*,25) CS,WS
      WRITE (10,25) CS,WS
   25 FORMAT (' CS = ',F6.3,5X,'WS = ',F7.1,' m^2')
      RT=0.5*1025*WS*(VS**2.0)*CT
      WRITE (*,*) ' SELECT ALLOWANCE FOR APPENDAGES IN % (10-25)'
      READ (*,*) APP
      RA=(APP/100.0)*RT
      RTA=RT+RA
      R=RTA/1000.0
      RW=RT/1000.0
      PE=R*VS
```

```
      PEW=RW*VS
      WRITE (*,26) R,PE
      WRITE (10,26) R,PE
   26 FORMAT (' RT = ',F6.1,' kN',5X,' PE = ',F7.1,' kW')
      WRITE (*,*) ' '
      WRITE (*,*) ' IF WATERJETS ARE INSTALLED,  THERE IS NO APPENDAGE'
      WRITE (*,*) ' DRAG. IN THIS CASE, TOTAL RESISTANCE AND EFFECTIVE'
      WRITE (*,*) ' HORSEPOWER ARE:'
      WRITE (*,26) RW,PEW
      DIAM=0.6*T
      WRITE (10,4003) DIAM
 4003 FORMAT (' D = ',F4.2,' m')
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT BLADE AREA RATIO, SHAFT ANGLE (DEG)'
      WRITE (*,*) ' AND NUMBER OF BLADES'
      READ (*,*) BAR,ALFA,Z
      FV=0.165*VS/(D**(1.0/6.0))
      WRITE (10,4004) FV
 4004 FORMAT (' FV = ',F5.3)
      IF ((FV.GE.0.58).AND.(FV.LE.2.76)) THEN
      WT=0.00343+0.11152*FV-0.27571*(FV**2.0)+0.16330*(FV**3.0)
     +  -0.02828*(FV**4.0)
      HR=0.81524+0.43985*FV-0.47333*(FV**2.0)+0.19918*(FV**3.0)
     +  -0.02351*(FV**4.0)-0.00201*(FV**5.0)
        ELSE
        WRITE (*,40)
        STOP
      ENDIF
   40 FORMAT (' VOLUMETRIC FROUDE NUMBER OUT OF RANGE')
      CALL TDCALC
      WRITE (10,4000) WT,TD
 4000 FORMAT (' WT = ',F7.4,5X,'TD = ',F7.4)
      HH=(1.0-TD)/(1.0-WT)
      WRITE (*,*) ' '
      WRITE (*,49) HH,HR
      WRITE (10,49) HH,HR
   49 FORMAT (' HULL EFF. = ',F5.3,5X,'REL. ROTATIVE EFF. = ',F5.3)
      CALL H0CALC
      QPC=HH*HR*H0
      PD=PE/QPC
      PB=PD/(HG*HS)
      WRITE (*,*) ' '
      WRITE (*,41) QPC
      WRITE (10,41) QPC
   41 FORMAT (' QUASI PROPULSIVE COEFFICIENT = ',F5.3)
      WRITE (*,*) ' '
      WRITE (*,42) PD,PB
      WRITE (10,42) PD,PB
   42 FORMAT (' DHP = ',F7.1,' kW',5X,'BHP = ',F7.1,' kW')
      QPCW=1.0/(1.0+(16.8/VSKN))
      PDW=PEW/QPCW
      PBW=PDW/(HG*HS)
      WRITE (*,*) ' '
      WRITE (*,*) ' IF WATERJETS ARE INSTALLED, THE QUASI PROPULSIVE'
      WRITE (*,76) QPCW
   76 FORMAT ('  COEFFICIENT IS: ',F5.3)
      WRITE (*,*) ' AND THE REQUIRED INSTALLED POWER IS:'
      WRITE (*,42) PDW,PBW
   15 WRITE (*,*) ' '
      WRITE (*,*) ' DO YOU WANT TO PERFORM CALCULATIONS FOR A'
      WRITE (*,*) ' DIFFERENT SPEED? (Y/N)'
      READ (*,55) YN2
      IF ((YN2.EQ.'Y').OR.(YN2.EQ.'y')) THEN
      GOTO 13
        ELSE IF ((YN2.NE.'N').AND.(YN2.NE.'n')) THEN
        WRITE (*,*) ' I SPECIFICALLY ASKED FOR AN Y OR AN N'
        GOTO 15
      ENDIF
   16 WRITE (*,*) ' '
      WRITE (*,*) ' DO YOU WANT TO PERFORM CALCULATIONS FOR'
      WRITE (*,*) ' ANOTHER VESSEL? (Y/N)'
      READ (*,55) YN3
      IF ((YN3.EQ.'Y').OR.(YN3.EQ.'y')) THEN
      GOTO 14
        ELSE IF ((YN3.NE.'N').AND.(YN3.NE.'n')) THEN
        WRITE (*,*) ' I SPECIFICALLY ASKED FOR AN Y OR AN N'
        GOTO 16
      ENDIF
```

```
   55 FORMAT (A)
      CLOSE (10)
      STOP
      END
C-----------------------------------------------------------------------
      SUBROUTINE CRCALCSO
      CHARACTER *6 SOTFILES(10)
      CHARACTER *6 FILES(4)
      REAL LD
      DIMENSION CRSOT(46,4),CRARR(4),CRARR2(2)
      DIMENSION FNSOT(46)
      COMMON/ONE/CR,FN,BONT,LD,CB
      SOTFILES(1)='3B.DAT'
      SOTFILES(2)='4A.DAT'
      SOTFILES(3)='4B.DAT'
      SOTFILES(4)='4C.DAT'
      SOTFILES(5)='5A.DAT'
      SOTFILES(6)='5B.DAT'
      SOTFILES(7)='5C.DAT'
      SOTFILES(8)='6A.DAT'
      SOTFILES(9)='6B.DAT'
      SOTFILES(10)='6C.DAT'
      CIRCM2=7.4
      CIRCM3=8.5
      CIRCM4=9.5
      BT1=1.5
      BT2=2.0
      BT3=2.5
      IF ((LD.GT.CIRCM3).AND.(LD.LE.CIRCM4)) THEN
      GOTO 35
        ELSE IF ((LD.GT.CIRCM2).AND.(LD.LE.CIRCM3)) THEN
        GOTO 36
          ELSE
          WRITE (*,38)
          STOP
      ENDIF
   35 IF ((BONT.GE.BT1).AND.(BONT.LE.BT2)) THEN
      FILES(1)=SOTFILES(5)
      FILES(2)=SOTFILES(6)
      FILES(3)=SOTFILES(8)
      FILES(4)=SOTFILES(9)
      GOTO 39
        ELSE IF ((BONT.GT.BT2).AND.(BONT.LE.BT3)) THEN
        FILES(1)=SOTFILES(6)
        FILES(2)=SOTFILES(7)
        FILES(3)=SOTFILES(9)
        FILES(4)=SOTFILES(10)
        GOTO 39
          ELSE
          WRITE (*,27)
          STOP
      ENDIF
   36 IF ((BONT.GE.BT1).AND.(BONT.LE.BT2)) THEN
      FILES(1)=SOTFILES(2)
      FILES(2)=SOTFILES(3)
      FILES(3)=SOTFILES(5)
      FILES(4)=SOTFILES(6)
      GOTO 39
        ELSE IF ((BONT.GT.BT2).AND.(BONT.LE.BT3)) THEN
        FILES(1)=SOTFILES(3)
        FILES(2)=SOTFILES(4)
        FILES(3)=SOTFILES(6)
        FILES(4)=SOTFILES(7)
        GOTO 39
          ELSE
          WRITE (*,27)
          STOP
      ENDIF
   39 DO 28 KF=1,4
      OPEN (KF,FILE=FILES(KF),STATUS='OLD')
   28 CONTINUE
      DO 29 KT=1,4
      DO 57 KFN=1,46
        READ (KT,30) FNSOT(KFN),CRSOT(KFN,KT)
   57   CONTINUE
   29 CONTINUE
      DO 33 KF2=1,4
      CLOSE (KF2)
```

```
 33 CONTINUE
    DO 19 KFN=1,46
    IF (FNSOT(KFN).GT.FN) THEN
      DO 58 INT=1,4
        CALL INTERP(FNSOT(KFN-1),FNSOT(KFN),CRSOT(KFN-1,INT),
   +      CRSOT(KFN,INT),FN,CRARR(INT))
 58     CONTINUE
      IF ((BONT.GE.BT1).AND.(BONT.LE.BT2)) THEN
        CALL INTERP(BT1,BT2,CRARR(1),CRARR(2),BONT,CRARR2(1))
        CALL INTERP(BT1,BT2,CRARR(3),CRARR(4),BONT,CRARR2(2))
          ELSE
          CALL INTERP(BT2,BT3,CRARR(1),CRARR(2),BONT,CRARR2(1))
          CALL INTERP(BT2,BT3,CRARR(3),CRARR(4),BONT,CRARR2(2))
      ENDIF
      IF ((LD.GT.CIRCM3).AND.(LD.LE.CIRCM4)) THEN
        CALL INTERP(CIRCM3,CIRCM4,CRARR2(1),CRARR2(2),LD,CR1)
          ELSE
          CALL INTERP(CIRCM2,CIRCM3,CRARR2(1),CRARR2(2),LD,CR1)
      ENDIF
      GOTO 61
    ENDIF
 19 CONTINUE
 61 CR=CR1/1000.0
 30 FORMAT (F6.4,F9.4)
 27 FORMAT (' B/T RATIO IS OUT OF RANGE')
 38 FORMAT (' L/D RATIO IS OUT OF RANGE')
    RETURN
    END
C-------------------------------------------------------------------------
    SUBROUTINE CRCALC64
    CHARACTER *12 SFFILES(3)
    REAL LD
    DIMENSION CRS64(3,25,9),CRARR(9,3),CRARR2(3,3),CRARR3(3)
    DIMENSION CIRCM1(3),CIRCM2(3),CIRCM3(3),FNS64(25)
    COMMON/ONE/CR,FN,BONT,LD,CB
    SFFILES(1)='SFTHIRTY.DAT'
    SFFILES(2)='SFFORTY.DAT'
    SFFILES(3)='SFFIFTY.DAT'
    CB1=0.35
    CB2=0.45
    CB3=0.55
    CIRCM1(1)=9.3
    CIRCM2(1)=10.5
    CIRCM3(1)=12.4
    CIRCM1(2)=8.6
    CIRCM2(2)=9.6
    CIRCM3(2)=11.3
    CIRCM1(3)=8.0
    CIRCM2(3)=8.9
    CIRCM3(3)=10.5
    DO 18 KCB=1,3
    OPEN (KCB,FILE=SFFILES(KCB),STATUS='OLD')
    DO 20 KLD=0,2
      DO 51 KFN=1,25
        READ (KCB,17) (CRS64(KCB,KFN,KBT),KBT=KLD*3+1,KLD*3+3)
 51     CONTINUE
 20   CONTINUE
    CLOSE (KCB)
    DO 19 KFN=1,25
      FNINI=KFN
      FNS64(KFN)=(FNINI/5.0)*0.297584
      IF (FNS64(KFN).GT.FN) THEN
        DO 21 INT=1,3
          CALL INTERP(FNS64(KFN-1),FNS64(KFN),CRS64(KCB,KFN-1,INT),
   +        CRS64(KCB,KFN,INT),FN,CRARR(INT,KCB))
          CALL INTERP(FNS64(KFN-1),FNS64(KFN),CRS64(KCB,KFN-1,INT+3)
   +        ,CRS64(KCB,KFN,INT+3),FN,CRARR(INT+3,KCB))
          CALL INTERP(FNS64(KFN-1),FNS64(KFN),CRS64(KCB,KFN-1,INT+6)
   +        ,CRS64(KCB,KFN,INT+6),FN,CRARR(INT+6,KCB))
 21       CONTINUE
        IF ((BONT.GE.2.0).AND.(BONT.LE.3.0)) THEN
          BT1=2.0
          BT2=3.0
          DO 22 INT2=0,2
        CALL INTERP(BT1,BT2,CRARR(INT2*3+1,KCB),
   +          CRARR(INT2*3+2,KCB),BONT,CRARR2(INT2+1,KCB))
 22         CONTINUE
        ELSE IF ((BONT.GT.3.0).AND.(BONT.LE.4.0)) THEN
```

```
      BT1=3.0
      BT2=4.0
      DO 23 INT2=0,2
        CALL INTERP(BT1,BT2,CRARR(INT2*3+2,KCB),
     +        CRARR(INT2*3+3,KCB),BONT,CRARR2(INT2+1,KCB))
 23         CONTINUE
        ELSE
        WRITE (*,*) ' B/T RATIO IS OUT OF RANGE'
        STOP
      ENDIF
      IF ((LD.GE.CIRCM1(KCB)).AND.(LD.LE.CIRCM2(KCB))) THEN
        CALL INTERP(CIRCM1(KCB),CIRCM2(KCB),CRARR2(1,KCB),
     +    CRARR2(2,KCB),LD,CRARR3(KCB))
      ELSE IF ((LD.GT.CIRCM2(KCB)).AND.(LD.LE.CIRCM3(KCB)))
     +      THEN
      CALL INTERP(CIRCM2(KCB),CIRCM3(KCB),CRARR2(2,KCB),
     +      CRARR2(3,KCB),LD,CRARR3(KCB))
        ELSE
        WRITE (*,*) ' L/D RATIO IS OUT OF RANGE'
        STOP
      ENDIF
      GOTO 18
    ENDIF
 19   CONTINUE
 18 CONTINUE
    CALL PARAB(CB1,CB2,CB3,CRARR3(1),CRARR3(2),CRARR3(3),CB,CR1)
    CR=CR1/1000.0
 17 FORMAT (3F7.3)
    RETURN
    END
C-----------------------------------------------------------------------
    SUBROUTINE CRCALCNP
    CHARACTER *12 NPLFILES(8)
    REAL LD
    INTEGER CASE(2)
    DIMENSION CRNPL(34,3,3,2),CRARR(3,3,2),CRARR2(3,2),CRARR3(2)
    DIMENSION FNNPL(34),CM1(7),CMA(3),CMB(3),BT(8,3,3)
    COMMON/ONE/CR,FN,BONT,LD,CB
    G=9.807
    NPLFILES(1)='NPLONE.DAT'
    NPLFILES(2)='NPLTWOA.DAT'
    NPLFILES(3)='NPLTWOB.DAT'
    NPLFILES(4)='NPLTHREA.DAT'
    NPLFILES(5)='NPLTHREB.DAT'
    NPLFILES(6)='NPLFOURA.DAT'
    NPLFILES(7)='NPLFOURB.DAT'
    NPLFILES(8)='NPLFIVE.DAT'
    CM1(1)=4.47
    CM1(2)=4.86
    CM1(3)=5.23
    CM1(4)=5.76
    CM1(5)=6.59
    CM1(6)=7.1
    CM1(7)=8.3
    OPEN (7,FILE='NPLBT.DAT',STATUS='OLD')
    DO 76 KF=1,8
    DO 77 KLD=1,3
      READ (7,78) (BT(KF,KLD,KBT),KBT=1,3)
 77   CONTINUE
 76 CONTINUE
 78 FORMAT (3F5.2)
    CLOSE (7)
    KTRAP=0
    IF ((LD.GE.CM1(1)).AND.(LD.LT.CM1(2))) THEN
    GOTO 62
      ELSE IF ((LD.GE.CM1(2)).AND.(LD.LT.CM1(3))) THEN
      GOTO 63
        ELSE IF ((LD.GE.CM1(3)).AND.(LD.LT.CM1(4))) THEN
        GOTO 64
          ELSE IF ((LD.GE.CM1(4)).AND.(LD.LT.CM1(5))) THEN
          GOTO 65
        ELSE IF ((LD.GE.CM1(5)).AND.(LD.LT.CM1(6))) THEN
        GOTO 66
          ELSE IF ((LD.GE.CM1(6)).AND.(LD.LE.CM1(7))) THEN
          GOTO 67
            ELSE
            WRITE (*,*) ' L/D RATIO IS OUT OF RANGE'
            STOP
```

```
   ENDIF
62 IF ((BONT.GE.2.19).AND.(BONT.LE.3.19)) THEN
   OPEN (1,FILE=NPLFILES(1),STATUS='OLD')
   CASE(1)=1
   CMA(1)=CM1(1)
   CMA(2)=CM1(2)
   CMA(3)=CM1(3)
   GOTO 68
     ELSE
     WRITE (*,69)
     STOP
   ENDIF
63 IF ((BONT.GE.2.19).AND.(BONT.LT.3.15)) THEN
   OPEN (1,FILE=NPLFILES(1),STATUS='OLD')
   OPEN (2,FILE=NPLFILES(2),STATUS='OLD')
   CASE(1)=1
   CASE(2)=2
   CMA(1)=CM1(1)
   CMA(2)=CM1(2)
   CMA(3)=CM1(3)
   CMB(1)=CM1(2)
   CMB(2)=CM1(3)
   CMB(3)=CM1(4)
   KTRAP=1
   GOTO 68
     ELSE IF ((BONT.GE.3.15).AND.(BONT.LE.3.19)) THEN
     OPEN (1,FILE=NPLFILES(1),STATUS='OLD')
     OPEN (2,FILE=NPLFILES(3),STATUS='OLD')
     CASE(1)=1
     CASE(2)=3
     CMA(1)=CM1(1)
     CMA(2)=CM1(2)
     CMA(3)=CM1(3)
     CMB(1)=CM1(2)
     CMB(2)=CM1(3)
     CMB(3)=CM1(4)
     KTRAP=1
     GOTO 68
       ELSE IF ((BONT.GT.3.19).AND.(BONT.LE.4.08)) THEN
       OPEN (1,FILE=NPLFILES(3),STATUS='OLD')
         CASE(1)=3
         CMA(1)=CM1(2)
         CMA(2)=CM1(3)
         CMA(3)=CM1(4)
         ELSE
         WRITE (*,69)
         STOP
   ENDIF
64 IF ((BONT.GE.2.01).AND.(BONT.LT.2.19)) THEN
   OPEN (1,FILE=NPLFILES(4),STATUS='OLD')
   CASE(1)=4
   CMA(1)=CM1(3)
   CMA(2)=CM1(4)
   CMA(3)=CM1(5)
   GOTO 68
     ELSE IF ((BONT.GE.2.19).AND.(BONT.LT.3.15)) THEN
     OPEN (1,FILE=NPLFILES(2),STATUS='OLD')
     OPEN (2,FILE=NPLFILES(4),STATUS='OLD')
     CASE(1)=2
     CASE(2)=4
     CMA(1)=CM1(2)
     CMA(2)=CM1(3)
     CMA(3)=CM1(4)
     CMB(1)=CM1(3)
     CMB(2)=CM1(4)
     CMB(3)=CM1(5)
     KTRAP=1
     GOTO 68
       ELSE IF ((BONT.GE.3.15).AND.(BONT.LT.3.3)) THEN
       OPEN (1,FILE=NPLFILES(3),STATUS='OLD')
       OPEN (2,FILE=NPLFILES(4),STATUS='OLD')
       CASE(1)=3
       CASE(2)=4
       CMA(1)=CM1(2)
       CMA(2)=CM1(3)
       CMA(3)=CM1(4)
       CMB(1)=CM1(3)
       CMB(2)=CM1(4)
```

```
      CMB(3)=CM1(5)
      KTRAP=1
      GOTO 68
        ELSE IF ((BONT.GE.3.3).AND.(BONT.LE.4.08)) THEN
        OPEN (1,FILE=NPLFILES(3),STATUS='OLD')
        OPEN (2,FILE=NPLFILES(5),STATUS='OLD')
        CASE(1)=3
        CASE(2)=5
        CMA(1)=CM1(2)
        CMA(2)=CM1(3)
        CMA(3)=CM1(4)
        CMB(1)=CM1(3)
        CMB(2)=CM1(4)
        CMB(3)=CM1(5)
        KTRAP=1
        GOTO 68
      ELSE IF ((BONT.GT.4.08).AND.(BONT.LE.5.1)) THEN
      OPEN (1,FILE=NPLFILES(5),STATUS='OLD')
      CASE(1)=5
      CMA(1)=CM1(3)
      CMA(2)=CM1(4)
      CMA(3)=CM1(5)
      GOTO 68
        ELSE
        WRITE (*,69)
        STOP
   ENDIF
65 IF ((BONT.GE.2.01).AND.(BONT.LT.2.51)) THEN
   OPEN (1,FILE=NPLFILES(4),STATUS='OLD')
   CASE(1)=4
   CMA(1)=CM1(3)
   CMA(2)=CM1(4)
   CMA(3)=CM1(5)
   GOTO 68
     ELSE IF ((BONT.GE.2.51).AND.(BONT.LT.3.3)) THEN
     OPEN (1,FILE=NPLFILES(4),STATUS='OLD')
     OPEN (2,FILE=NPLFILES(6),STATUS='OLD')
     CASE(1)=4
     CASE(2)=6
     CMA(1)=CM1(3)
     CMA(2)=CM1(4)
     CMA(3)=CM1(5)
     CMB(1)=CM1(4)
     CMB(2)=CM1(5)
     CMB(3)=CM1(6)
     KTRAP=1
     GOTO 68
       ELSE IF ((BONT.GE.3.3).AND.(BONT.LT.3.65)) THEN
       OPEN (1,FILE=NPLFILES(5),STATUS='OLD')
       OPEN (2,FILE=NPLFILES(6),STATUS='OLD')
       CASE(1)=5
       CASE(2)=6
       CMA(1)=CM1(3)
       CMA(2)=CM1(4)
       CMA(3)=CM1(5)
       CMB(1)=CM1(4)
       CMB(2)=CM1(5)
       CMB(3)=CM1(6)
       KTRAP=1
       GOTO 68
         ELSE IF ((BONT.GE.3.65).AND.(BONT.LT.5.1)) THEN
         OPEN (1,FILE=NPLFILES(5),STATUS='OLD')
         OPEN (2,FILE=NPLFILES(7),STATUS='OLD')
         CASE(1)=5
         CASE(2)=7
         CMA(1)=CM1(3)
         CMA(2)=CM1(4)
         CMA(3)=CM1(5)
         CMB(1)=CM1(4)
         CMB(2)=CM1(5)
         CMB(3)=CM1(6)
         KTRAP=1
         GOTO 68
       ELSE IF ((BONT.GE.5.1).AND.(BONT.LE.5.49)) THEN
       OPEN (1,FILE=NPLFILES(7),STATUS='OLD')
       CASE(1)=7
       CMA(1)=CM1(4)
       CMA(2)=CM1(5)
```

```
        CMA(3)=CM1(6)
        GOTO 68
          ELSE
          WRITE (*,69)
          STOP
    ENDIF
 66 IF ((BONT.GE.2.51).AND.(BONT.LT.3.65)) THEN
    OPEN (1,FILE=NPLFILES(6),STATUS='OLD')
    CASE(1)=6
    CMA(1)=CM1(4)
    CMA(2)=CM1(5)
    CMA(3)=CM1(6)
    GOTO 68
      ELSE IF ((BONT.GE.3.65).AND.(BONT.LT.4.02)) THEN
      OPEN (1,FILE=NPLFILES(7),STATUS='OLD')
      CASE(1)=7
      CMA(1)=CM1(4)
      CMA(2)=CM1(5)
      CMA(3)=CM1(6)
      GOTO 68
        ELSE IF ((BONT.GE.4.02).AND.(BONT.LE.5.49)) THEN
        OPEN (1,FILE=NPLFILES(7),STATUS='OLD')
        OPEN (2,FILE=NPLFILES(8),STATUS='OLD')
        CASE(1)=7
        CASE(2)=8
        CMA(1)=CM1(4)
        CMA(2)=CM1(5)
        CMA(3)=CM1(6)
        CMB(1)=CM1(5)
        CMB(2)=CM1(6)
        CMB(3)=CM1(7)
        KTRAP=1
        GOTO 68
          ELSE
          WRITE (*,69)
          STOP
    ENDIF
 67 IF ((BONT.GE.4.02).AND.(BONT.LE.5.49)) THEN
    OPEN (1,FILE=NPLFILES(8),STATUS='OLD')
    CASE(1)=8
    CMA(1)=CM1(5)
    CMA(2)=CM1(6)
    CMA(3)=CM1(7)
    GOTO 68
      ELSE
      WRITE (*,69)
      STOP
    ENDIF
 68 IF (KTRAP.EQ.0) THEN
    DO 70 KLD=1,3
      DO 71 KFN=1,34
        READ (1,75) (CRNPL(KFN,KLD,KBT,1),KBT=1,3)
 71     CONTINUE
 70   CONTINUE
      ELSE
      DO 72 KT=1,2
        DO 73 KLD=1,3
          DO 74 KFN=1,34
        READ (KT,75) (CRNPL(KFN,KLD,KBT,KT),KBT=1,3)
 74         CONTINUE
 73       CONTINUE
 72     CONTINUE
    ENDIF
 75 FORMAT (3F7.4)
    CLOSE (1)
    IF (KTRAP.EQ.1) THEN
    CLOSE (2)
    ENDIF
    DO 79 KVL=1,34
    RVL=KVL
    VL=0.8+((RVL-1.0)*0.1)
    FNNPL(KVL)=VL*0.297584
    IF (FNNPL(KVL).GT.FN) THEN
      DO 80 KLD=1,3
        DO 81 KBT=1,3
          CALL INTERP(FNNPL(KVL-1),FNNPL(KVL),CRNPL(KVL-1,KLD,KBT,1)
  +         ,CRNPL(KVL,KLD,KBT,1),FN,CRARR(KLD,KBT,1))
 81       CONTINUE
```

```
 80     CONTINUE
      IF (KTRAP.EQ.1) THEN
        DO 82 KLD=1,3
          DO 83 KBT=1,3
        CALL INTERP(FNNPL(KVL-1),FNNPL(KVL),CRNPL(KVL-1,KLD,
     +          KBT,2),CRNPL(KVL,KLD,KBT,2),FN,CRARR(KLD,KBT,2))
 83         CONTINUE
 82       CONTINUE
      ENDIF
      DO 84 KLD=1,3
        CALL PARAB(BT(CASE(1),KLD,1),BT(CASE(1),KLD,2),
     +    BT(CASE(1),KLD,3),CRARR(KLD,1,1),CRARR(KLD,2,1),
     +    CRARR(KLD,3,1),BONT,CRARR2(KLD,1))
 84     CONTINUE
      IF (KTRAP.EQ.1) THEN
        DO 85 KLD=1,3
          CALL PARAB(BT(CASE(2),KLD,1),BT(CASE(2),KLD,2),
     +      BT(CASE(2),KLD,3),CRARR(KLD,1,2),CRARR(KLD,2,2),
     +      CRARR(KLD,3,2),BONT,CRARR2(KLD,2))
 85       CONTINUE
      ENDIF
      CALL PARAB(CMA(1),CMA(2),CMA(3),CRARR2(1,1),CRARR2(2,1),
     +  CRARR2(3,1),LD,CRARR3(1))
      IF (KTRAP.EQ.1) THEN
        CALL PARAB(CMB(1),CMB(2),CMB(3),CRARR2(1,2),CRARR2(2,2),
     +    CRARR2(3,2),LD,CRARR3(2))
        CR1=(CRARR3(1)+CRARR3(2))/2.0
          ELSE
          CR1=CRARR3(1)
      ENDIF
      GOTO 86
    ENDIF
 79 CONTINUE
 86 CR=CR1/1000.0
 69 FORMAT (' B/T RATIO OUT IS OUT OF RANGE')
    RETURN
    END
C------------------------------------------------------------------------
    SUBROUTINE TDCALC
    COMMON/TWO/ALFA,FV
    COMMON/FOUR/TD
    A1=7.0
    A2=11.0
    A3=16.0
    TD7=0.43803-0.92242*FV+0.81950*(FV**2.0)-0.32145*(FV**3.0)
   ++0.04659*(FV**4.0)
    TD11=0.36479-0.68502*FV+0.69963*(FV**2.0)-0.34875*(FV**3.0)
   ++0.06700*(FV**4.0)
    TD16=0.41018-0.47956*FV+0.22567*(FV**2.0)-0.03129*(FV**3.0)
    IF ((ALFA.GE.7.0).AND.(ALFA.LT.11.0)) THEN
    CALL INTERP(A1,A2,TD7,TD11,ALFA,TD)
      ELSE IF ((ALFA.GE.11.0).AND.(ALFA.LE.16.0)) THEN
      CALL INTERP(A2,A3,TD11,TD16,ALFA,TD)
        ELSE
        WRITE (*,*) ' SHAFT ANGLE OUT OF RANGE'
        STOP
    ENDIF
    RETURN
    END
C------------------------------------------------------------------------
    SUBROUTINE HOCALC
    REAL J,KT,KQ,KT1
    INTEGER Z
    CHARACTER *1 PRSER
    CHARACTER *11 KTFILE,KQFILE
    DIMENSION HOARR(0:100),HOOPT(0:10)
    DIMENSION CNKT(39),SKT(39),TKT(39),UKT(39),VKT(39)
    DIMENSION CNKQ(47),SKQ(47),TKQ(47),UKQ(47),VKQ(47)
    COMMON/FOUR/TD
    COMMON/THREE/HO,DIAM,WT,BAR,Z,RTA,VS
    PI=3.14159
    SREV=0.2
    HOARR(0)=0.0
    HOOPT(0)=0.0
    THRUST=((RTA/2.0)/(1.0-TD))
    WRITE (10,4005) THRUST
4005 FORMAT (' THRUST PER SHAFT = ',F9.1,' N')
    RPS=SQRT(THRUST/(0.2*1025*(DIAM**4.0)))
```

```
      WRITE (10,4014) RPS
   44 WRITE (*,*) ' '
      WRITE (*,*) ' SELECT PROPELLER SERIES TO BE USED'
      WRITE (*,*) ' (W)AGENINGEN-B OR (G)AWN'
      READ (*,52) PRSER
   52 FORMAT (A)
      IF ((PRSER.EQ.'W').OR.(PRSER.EQ.'w')) THEN
      KTFILE='WAGENKT.DAT'
      KQFILE='WAGENKQ.DAT'
        ELSE IF ((PRSER.EQ.'G').OR.(PRSER.EQ.'g')) THEN
        KTFILE='GAWNKT.DAT'
        KQFILE='GAWNKQ.DAT'
          ELSE
          WRITE (*,*) ' I SPECIFICALLY ASKED FOR A "W" OR A "G"'
          GOTO 44
      ENDIF
      OPEN (5,FILE=KTFILE,STATUS='OLD')
      OPEN (6,FILE=KQFILE,STATUS='OLD')
      VA=VS*(1.0-WT)
      WRITE (10,4006) VA
 4006 FORMAT (' VA = ',F5.2,' m/s')
      DO 45 KKT=1,39
      READ (5,*) CNKT(KKT),SKT(KKT),TKT(KKT),UKT(KKT),VKT(KKT)
   45 CONTINUE
      DO 47 KKQ=1,47
      READ (6,*) CNKQ(KKQ),SKQ(KKQ),TKQ(KKQ),UKQ(KKQ),VKQ(KKQ)
   47 CONTINUE
      KH0=1
      KTRAP=0
      KOPT=1
   43 J=VA/(RPS*DIAM)
      KT1=THRUST/(1025*(RPS**2.0)*(DIAM**4.0))
      WRITE (10,4007) J,KT1
 4007 FORMAT (' J = ',F5.3,5X,' KT1 = ',F9.5)
      PD=1.0
   46 KT=0.0
      FKT=0.0
      DO 53 KKT=1,39
      KT=KT+(CNKT(KKT)*(J**SKT(KKT))*(PD**TKT(KKT))*(BAR**UKT(KKT))
     +  *(Z**VKT(KKT)))
      FKT=FKT+(CNKT(KKT)*(J**SKT(KKT))*TKT(KKT)*(PD**(TKT(KKT)-1.0))
     +  *(BAR**UKT(KKT))*(Z**VKT(KKT)))
   53 CONTINUE
      WRITE (10,4008) KT
 4008 FORMAT (' KT = ',F9.5)
      DIFFKT=ABS(KT-KT1)
      WRITE (10,4009) DIFFKT
 4009 FORMAT (' DIFFKT = ',F9.5)
      IF (DIFFKT.GT.0.0001) THEN
      WRITE (10,4010) PD
      PD=PD-((KT-KT1)/FKT)
      WRITE (10,4010) PD
      GOTO 46
      ENDIF
 4010 FORMAT (' P/D = ',F7.4)
      KQ=0.0
      DO 54 KKQ=1,47
      KQ=KQ+(CNKQ(KKQ)*(J**SKQ(KKQ))*(PD**TKQ(KKQ))*(BAR**UKQ(KKQ))
     +  *(Z**VKQ(KKQ)))
   54 CONTINUE
      WRITE (10,4011) KQ
 4011 FORMAT (' KQ = ',F9.5)
      H0ARR(KH0)=(J*KT)/(2.0*PI*KQ)
      WRITE (10,4012) KH0,H0ARR(KH0)
 4012 FORMAT (' H0(',I2,') = ',F6.4)
      IF (KTRAP.EQ.1) THEN
      H0OPT(KOPT)=H0ARR(KH0)
      WRITE (10,4013) KOPT,H0OPT(KOPT)
      GOTO 48
      ENDIF
 4013 FORMAT (' H0OPT(',I1,') = ',F6.4)
      IF (H0ARR(KH0).LT.H0ARR(KH0-1)) THEN
      CALL QUADRA(H0ARR(KH0-2),H0ARR(KH0-1),H0ARR(KH0),SREV,
     +  RPS-SREV,RPSOPT)
      RPS=RPSOPT
      WRITE (10,4014) RPS
      KH0=KH0+1
      KTRAP=1
```

```
      GOTO 43
      ENDIF
 4014 FORMAT (' n = ',F6.3,' rps')
      RPS=RPS+SREV
      WRITE (10,4014) RPS
      KH0=KH0+1
      GOTO 43
   48 DIFFH0=ABS(H0OPT(KOPT)-H0OPT(KOPT-1))
      WRITE (10,4015) DIFFH0
 4015 FORMAT (' DIFFH0 = ',F7.5)
      IF (DIFFH0.GT.0.0001) THEN
      RPS=RPS-SREV
      WRITE (10,4014) RPS
      SREV=SREV/3.0
      WRITE (10,4016) SREV
      KTRAP=0
      KH0=1
      KOPT=KOPT+1
      GOTO 43
        ELSE
        H0=H0OPT(KOPT)
      ENDIF
 4016 FORMAT (' STEP = ',F5.3,' rps')
      CLOSE (5)
      CLOSE (6)
      RPM=RPS*60.0
      WRITE (*,*) ' '
      WRITE (10,4010) PD
      WRITE (*,50) H0,RPM
      WRITE (10,50) H0,RPM
   50 FORMAT (' OPTIMUM OPEN WATER EFF. = ',F5.3,5X,'AT ',F6.1,' rpm')
      RETURN
      END
C-----------------------------------------------------------------------
      SUBROUTINE INTERP(XA,XB,YA,YB,XM,YM)
      DX=XB-XA
      DY=YB-YA
      HX=XM-XA
      RX=HX/DX
      YM=YA+(RX*DY)
      RETURN
      END
C-----------------------------------------------------------------------
      SUBROUTINE PARAB(X1,X2,X3,Y1,Y2,Y3,X,Y)
      QUAD(X)=A+(B*X)+(C*(X**2.0))
      D=(X2*(X3**2.0)-X3*(X2**2.0))-X1*(X3**2.0-X2**2.0)
     ++(X1**2.0)*(X3-X2)
      A=(Y1*(X2*(X3**2.0)-X3*(X2**2.0))-X1*(Y2*(X3**2.0)-Y3*(X2**2.0))
     ++(X1**2.0)*(Y2*X3-Y3*X2))/D
      B=((Y2*(X3**2.0)-Y3*(X2**2.0))-Y1*(X3**2.0-X2**2.0)
     ++(X1**2.0)*(Y3-Y2))/D
      C=(X2*Y3-X3*Y2-X1*(Y3-Y2)+Y1*(X3-X2))/D
      Y=QUAD(X)
      RETURN
      END
C-----------------------------------------------------------------------
      SUBROUTINE QUADRA(Y1,Y2,Y3,S,X2,XR)
      SM=S*(Y1-Y3)/(2.0*(Y1-2.0*Y2+Y3))
      XR=X2+SM
      RETURN
      END
```

```
      PROGRAM CATPOWER
      REAL LWL,LDRATIO,NI,LD
      INTEGER Z
      CHARACTER *1 YN2,YN3,RESER
      COMMON/ONE/CR,FN,BONT,LD,CB,SLWL
      COMMON/TWO/ALFA,FV
      COMMON/THREE/H0,DIAM,WT,BAR,Z,RTA,VS
      COMMON/FOUR/TD
      G=9.807
      NI=1.18831E-6
      CB=0.4
      HG=0.97
      HS=0.97
      OPEN (10,FILE='CAT.OUT',STATUS='NEW')
      WRITE (*,*) ' '
      WRITE (*,*) '**************************************************'
      WRITE (*,*) ' '
      WRITE (*,*) ' PRELIMINARY ESTIMATION OF REQUIRED INSTALLED'
      WRITE (*,*) ' POWER FOR HIGH-SPEED CATAMARAN FERRIES'
   14 WRITE (*,*) ' '
      WRITE (*,*) '**************************************************'
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT VESSEL''S MAIN DIMENSIONS IN THE FOLLOWING'
      WRITE (*,*) ' ORDER: LWL, BH, T, S'
      READ (*,*) LWL,BH,T,S
      BONT=BH/T
      DVOL=LWL*BH*2.0*T*CB
      D=DVOL*1.025
      LDRATIO=LWL/(DVOL**(1.0/3.0))
      LD=LDRATIO*(2.0**(1.0/3.0))
      SLWL=S/LWL
      WRITE (10,4001) D,LD,SLWL
 4001 FORMAT (' DISP. = ',F6.1,' t',5X,'L/DISP = ',F5.2,5X,'S/L = 'F5.3)
   13 WRITE (*,*) ' '
      WRITE (*,*) ' INPUT SPEED FOR WHICH TO PERFORM CALCULATIONS (KN)'
      READ (*,*) VSKN
      VS=VSKN*0.5145
      FN=VS/SQRT(G*LWL)
      RN=LWL*VS/NI
      WRITE (10,4002) VS,FN,RN
 4002 FORMAT (' VS = ',F5.2,' m/s',5X,'FN = ',F5.3,5X,'RN = ',E11.4)
   57 WRITE (*,*) ' '
      WRITE (*,*) ' SELECT SERIES TO BE USED FOR RESISTANCE CALCULATION'
      WRITE (*,*) ' SOUTHAMPTON EXTENDED (N)PL OR (S)ERIES-64'
      READ (*,55) RESER
      IF ((RESER.EQ.'N').OR.(RESER.EQ.'n')) THEN
      CALL CRCALCNP
        ELSE IF ((RESER.EQ.'S').OR.(RESER.EQ.'s')) THEN
        CALL CRCALC64
          ELSE
          WRITE (*,*) ' I SPECIFICALLY ASKED FOR AN "N" OR AN "S"'
          GOTO 57
      ENDIF
      CF=(0.075/((ALOG10(RN)-2.0)**2.0))
      CT=CF+CR
      WRITE (*,24) CR,CF,CT
      WRITE (10,24) CR,CF,CT
   24 FORMAT (' CR = ',E14.4,5X,'CF = ',E14.4,5X,'CT = ',E14.4)
      IF ((RESER.EQ.'S').OR.(RESER.EQ.'s')) THEN
      CS=6.554423597-1.225559486*BONT+0.2161030028*(BONT**2.0)
     +    -15.40884518*CB+4.4468108569*BONT*CB-0.6940997418*(BONT**2.0)*CB
     +    +15.40377259*(CB**2.0)-4.527288815*BONT*(CB**2.0)
     +    +0.6552098659*((BONT*CB)**2.0)
        ELSE
        CS=2.5380616+0.049355*BONT+0.013070129*(BONT**2.0)
      ENDIF
      WS=CS*SQRT(LWL*(DVOL/2.0))*2.0
      WRITE (*,25) CS,WS
      WRITE (10,25) CS,WS
   25 FORMAT (' CS = ',F6.3,5X,'WS = ',F7.1,' m^2')
      RT=0.5*1025*WS*(VS**2.0)*CT
      WRITE (*,*) ' SELECT ALLOWANCE FOR APPENDAGES IN % (10-25)'
      READ (*,*) APP
      RA=(APP/100.0)*RT
      RTA=RT+RA
      R=RTA/1000.0
      RW=RT/1000.0
      PE=R*VS
```

```
      PEW=RW*VS
      WRITE (*,26) R,PE
      WRITE (10,26) R,PE
   26 FORMAT (' RT = ',F6.1,' kN',5X,' PE = ',F7.1,' kW')
      WRITE (*,*) ' '
      WRITE (*,*) ' IF WATERJETS ARE INSTALLED,  THERE IS NO APPENDAGE'
      WRITE (*,*) ' DRAG. IN THIS CASE, TOTAL RESISTANCE AND EFFECTIVE'
      WRITE (*,*) ' HORSEPOWER ARE:'
      WRITE (*,26) RW,PEW
      DIAM=0.6*T
      WRITE (10,4003) DIAM
 4003 FORMAT (' D = ',F4.2,' m')
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT BLADE AREA RATIO, SHAFT ANGLE (DEG)'
      WRITE (*,*) ' AND NUMBER OF BLADES'
      READ (*,*) BAR,ALFA,Z
      FV=0.165*VS/(D**(1.0/6.0))
      WRITE (10,4004) FV
 4004 FORMAT (' FV = ',F5.3)
      IF ((FV.GE.0.58).AND.(FV.LE.2.76)) THEN
      WT=0.00343+0.11152*FV-0.27571*(FV**2.0)+0.16330*(FV**3.0)
     +    -0.02828*(FV**4.0)
      HR=0.81524+0.43985*FV-0.47333*(FV**2.0)+0.19918*(FV**3.0)
     +    -0.02351*(FV**4.0)-0.00201*(FV**5.0)
        ELSE
        WRITE (*,40)
        STOP
      ENDIF
   40 FORMAT (' VOLUMETRIC FROUDE NUMBER OUT OF RANGE')
      CALL TDCALC
      WRITE (10,4000) WT,TD
 4000 FORMAT (' WT = ',F7.4,5X,'TD = ',F7.4)
      HH=(1.0-TD)/(1.0-WT)
      WRITE (*,*) ' '
      WRITE (*,49) HH,HR
      WRITE (10,49) HH,HR
   49 FORMAT (' HULL EFF. = ',F5.3,5X,'REL. ROTATIVE EFF. = ',F5.3)
      CALL H0CALC
      QPC=HH*HR*H0
      PD=PE/QPC
      PB=PD/(HG*HS)
      WRITE (*,*) ' '
      WRITE (*,41) QPC
      WRITE (10,41) QPC
   41 FORMAT (' QUASI PROPULSIVE COEFFICIENT = ',F5.3)
      WRITE (*,*) ' '
      WRITE (*,42) PD,PB
      WRITE (10,42) PD,PB
   42 FORMAT (' DHP = ',F7.1,' kW',5X,'BHP = ',F7.1,' kW')
      QPCW=1.0/(1.0+(16.8/VSKN))
      PDW=PEW/QPCW
      PBW=PDW/(HG*HS)
      WRITE (*,*) ' '
      WRITE (*,*) ' IF WATERJETS ARE INSTALLED, THE QUASI PROPULSIVE'
      WRITE (*,76) QPCW
   76 FORMAT ('  COEFFICIENT IS: ',F5.3)
      WRITE (*,*) ' AND THE REQUIRED INSTALLED POWER IS:'
      WRITE (*,42) PDW,PBW
   15 WRITE (*,*) ' '
      WRITE (*,*) ' DO YOU WANT TO PERFORM CALCULATIONS FOR A'
      WRITE (*,*) ' DIFFERENT SPEED? (Y/N)'
      READ (*,55) YN2
      IF ((YN2.EQ.'Y').OR.(YN2.EQ.'y')) THEN
      GOTO 13
        ELSE IF ((YN2.NE.'N').AND.(YN2.NE.'n')) THEN
        WRITE (*,*) ' I SPECIFICALLY ASKED FOR AN Y OR AN N'
        GOTO 15
      ENDIF
   16 WRITE (*,*) ' '
      WRITE (*,*) ' DO YOU WANT TO PERFORM CALCULATIONS FOR'
      WRITE (*,*) ' ANOTHER VESSEL? (Y/N)'
      READ (*,55) YN3
      IF ((YN3.EQ.'Y').OR.(YN3.EQ.'y')) THEN
      GOTO 14
        ELSE IF ((YN3.NE.'N').AND.(YN3.NE.'n')) THEN
        WRITE (*,*) ' I SPECIFICALLY ASKED FOR AN Y OR AN N'
        GOTO 16
      ENDIF
```

```
   55 FORMAT (A)
      CLOSE (10)
      STOP
      END
C-----------------------------------------------------------------------
      SUBROUTINE CRCALCNP
      CHARACTER *6 NPLFILES(10)
      CHARACTER *6 FILES(4)
      REAL LD
      DIMENSION CRNPL(46,4,5),CRARR(4,4),CRARR2(4),CRARR3(2)
      DIMENSION FNNPL(46)
      COMMON/ONE/CR,FN,BONT,LD,CB,SLWL
      NPLFILES(1)='3B.DAT'
      NPLFILES(2)='4A.DAT'
      NPLFILES(3)='4B.DAT'
      NPLFILES(4)='4C.DAT'
      NPLFILES(5)='5A.DAT'
      NPLFILES(6)='5B.DAT'
      NPLFILES(7)='5C.DAT'
      NPLFILES(8)='6A.DAT'
      NPLFILES(9)='6B.DAT'
      NPLFILES(10)='6C.DAT'
      CIRCM2=7.4
      CIRCM3=8.5
      CIRCM4=9.5
      BT1=1.5
      BT2=2.0
      BT3=2.5
      SL1=0.2
      SL2=0.3
      SL3=0.4
      SL4=0.5
      IF ((LD.GT.CIRCM3).AND.(LD.LE.CIRCM4)) THEN
      GOTO 35
        ELSE IF ((LD.GT.CIRCM2).AND.(LD.LE.CIRCM3)) THEN
        GOTO 36
          ELSE
          WRITE (*,38)
          STOP
      ENDIF
   35 IF ((BONT.GE.BT1).AND.(BONT.LE.BT2)) THEN
      FILES(1)=NPLFILES(5)
      FILES(2)=NPLFILES(6)
      FILES(3)=NPLFILES(8)
      FILES(4)=NPLFILES(9)
      GOTO 39
        ELSE IF ((BONT.GT.BT2).AND.(BONT.LE.BT3)) THEN
        FILES(1)=NPLFILES(6)
        FILES(2)=NPLFILES(7)
        FILES(3)=NPLFILES(9)
        FILES(4)=NPLFILES(10)
        GOTO 39
          ELSE
          WRITE (*,27)
          STOP
      ENDIF
   36 IF ((BONT.GE.BT1).AND.(BONT.LE.BT2)) THEN
      FILES(1)=NPLFILES(2)
      FILES(2)=NPLFILES(3)
      FILES(3)=NPLFILES(5)
      FILES(4)=NPLFILES(6)
      GOTO 39
        ELSE IF ((BONT.GT.BT2).AND.(BONT.LE.BT3)) THEN
        FILES(1)=NPLFILES(3)
        FILES(2)=NPLFILES(4)
        FILES(3)=NPLFILES(6)
        FILES(4)=NPLFILES(7)
        GOTO 39
          ELSE
          WRITE (*,27)
          STOP
      ENDIF
   39 DO 28 KF=1,4
      OPEN (KF,FILE=FILES(KF),STATUS='OLD')
   28 CONTINUE
      DO 29 KT=1,4
      DO 51 KFN=1,46
        READ (KT,30) FNNPL(KFN),(CRNPL(KFN,KT,KSL),KSL=1,5)
```

```
   51 CONTINUE
   29 CONTINUE
      DO 33 KF2=1,4
      CLOSE (KF2)
   33 CONTINUE
      DO 19 KFN=1,46
      IF (FNNPL(KFN).GT.FN) THEN
        DO 21 INT=1,4
          CALL INTERP(FNNPL(KFN-1),FNNPL(KFN),CRNPL(KFN-1,INT,2),
     +         CRNPL(KFN,INT,2),FN,CRARR(INT,1))
          CALL INTERP(FNNPL(KFN-1),FNNPL(KFN),CRNPL(KFN-1,INT,3),
     +         CRNPL(KFN,INT,3),FN,CRARR(INT,2))
          CALL INTERP(FNNPL(KFN-1),FNNPL(KFN),CRNPL(KFN-1,INT,4),
     +         CRNPL(KFN,INT,4),FN,CRARR(INT,3))
          CALL INTERP(FNNPL(KFN-1),FNNPL(KFN),CRNPL(KFN-1,INT,5),
     +         CRNPL(KFN,INT,5),FN,CRARR(INT,4))
   21   CONTINUE
        IF ((SLWL.GE.SL1).AND.(SLWL.LE.SL2)) THEN
          DO 22 INT2=1,4
            CALL INTERP(SL1,SL2,CRARR(INT2,1),
     +           CRARR(INT2,2),SLWL,CRARR2(INT2))
   22     CONTINUE
            ELSE IF ((SLWL.GT.SL2).AND.(SLWL.LE.SL3)) THEN
            DO 23 INT2=1,4
          CALL INTERP(SL2,SL3,CRARR(INT2,2),
     +         CRARR(INT2,3),SLWL,CRARR2(INT2))
   23       CONTINUE
          ELSE IF ((SLWL.GT.SL3).AND.(SLWL.LE.SL4)) THEN
          DO 34 INT2=1,4
            CALL INTERP(SL3,SL4,CRARR(INT2,3),
     +           CRARR(INT2,4),SLWL,CRARR2(INT2))
   34     CONTINUE
            ELSE
            WRITE (*,*) ' S/LWL RATIO IS OUT OF RANGE'
            STOP
        ENDIF
        IF ((BONT.GE.BT1).AND.(BONT.LE.BT2)) THEN
          CALL INTERP(BT1,BT2,CRARR2(1),CRARR2(2),BONT,CRARR3(1))
          CALL INTERP(BT1,BT2,CRARR2(3),CRARR2(4),BONT,CRARR3(2))
            ELSE
            CALL INTERP(BT2,BT3,CRARR2(1),CRARR2(2),BONT,CRARR3(1))
            CALL INTERP(BT2,BT3,CRARR2(3),CRARR2(4),BONT,CRARR3(2))
        ENDIF
        IF ((LD.GT.CIRCM3).AND.(LD.LE.CIRCM4)) THEN
          CALL INTERP(CIRCM3,CIRCM4,CRARR3(1),CRARR3(2),LD,CR1)
            ELSE
            CALL INTERP(CIRCM2,CIRCM3,CRARR3(1),CRARR3(2),LD,CR1)
        ENDIF
        GOTO 56
      ENDIF
   19 CONTINUE
   56 CR=CR1/1000.0
   30 FORMAT (F6.4,5F9.4)
   27 FORMAT (' B/T RATIO IS OUT OF RANGE')
   38 FORMAT (' L/D RATIO IS OUT OF RANGE')
      RETURN
      END
C-------------------------------------------------------------------------
      SUBROUTINE CRCALC64
      CHARACTER *11 SFFILES(3,3,3)
      CHARACTER *11 FILES(4,3)
      REAL LD
      DIMENSION CR64(25,4,5,3),CRARR(4,4,3),CRARR2(4,3),CRARR3(2,3)
      DIMENSION CRARR4(3)
      DIMENSION FNS64(25),CIRCM(3,3)
      COMMON/ONE/CR,FN,BONT,LD,CB,SLWL
      SFFILES(1,1,1)='CB035A2.DAT'
      SFFILES(1,1,2)='CB035A3.DAT'
      SFFILES(1,1,3)='CB035A4.DAT'
      SFFILES(1,2,1)='CB035B2.DAT'
      SFFILES(1,2,2)='CB035B3.DAT'
      SFFILES(1,2,3)='CB035B4.DAT'
      SFFILES(1,3,1)='CB035C2.DAT'
      SFFILES(1,3,2)='CB035C3.DAT'
      SFFILES(1,3,3)='CB035C4.DAT'
      SFFILES(2,1,1)='CB045A2.DAT'
      SFFILES(2,1,2)='CB045A3.DAT'
      SFFILES(2,1,3)='CB045A4.DAT'
```

```
      SFFILES(2,2,1)='CB045B2.DAT'
      SFFILES(2,2,2)='CB045B3.DAT'
      SFFILES(2,2,3)='CB045B4.DAT'
      SFFILES(2,3,1)='CB045C2.DAT'
      SFFILES(2,3,2)='CB045C3.DAT'
      SFFILES(2,3,3)='CB045C4.DAT'
      SFFILES(3,1,1)='CB055A2.DAT'
      SFFILES(3,1,2)='CB055A3.DAT'
      SFFILES(3,1,3)='CB055A4.DAT'
      SFFILES(3,2,1)='CB055B2.DAT'
      SFFILES(3,2,2)='CB055B3.DAT'
      SFFILES(3,2,3)='CB055B4.DAT'
      SFFILES(3,3,1)='CB055C2.DAT'
      SFFILES(3,3,2)='CB055C3.DAT'
      SFFILES(3,3,3)='CB055C4.DAT'
      CIRCM(1,1)=9.3
      CIRCM(1,2)=10.5
      CIRCM(1,3)=12.4
      CIRCM(2,1)=8.6
      CIRCM(2,2)=9.6
      CIRCM(2,3)=11.3
      CIRCM(3,1)=8.0
      CIRCM(3,2)=8.9
      CIRCM(3,3)=10.5
      BT1=2.0
      BT2=3.0
      BT3=4.0
      SL1=0.2
      SL2=0.3
      SL3=0.4
      SL4=0.5
      CB1=0.35
      CB2=0.45
      CB3=0.55
      DO 58 KCB=1,3
      IF ((LD.GT.CIRCM(KCB,1)).AND.(LD.LE.CIRCM(KCB,2))) THEN
        GOTO 59
          ELSE IF ((LD.GE.CIRCM(KCB,2)).AND.(LD.LE.CIRCM(KCB,3))) THEN
          GOTO 60
            ELSE
            WRITE (*,62)
            STOP
      ENDIF
   59 IF ((BONT.GE.BT1).AND.(BONT.LE.BT2)) THEN
        FILES(1,KCB)=SFFILES(KCB,1,1)
        FILES(2,KCB)=SFFILES(KCB,1,2)
        FILES(3,KCB)=SFFILES(KCB,2,1)
        FILES(4,KCB)=SFFILES(KCB,2,2)
        GOTO 63
          ELSE IF ((BONT.GT.BT2).AND.(BONT.LE.BT3)) THEN
          FILES(1,KCB)=SFFILES(KCB,1,2)
          FILES(2,KCB)=SFFILES(KCB,1,3)
          FILES(3,KCB)=SFFILES(KCB,2,2)
          FILES(4,KCB)=SFFILES(KCB,2,3)
          GOTO 63
            ELSE
            WRITE (*,64)
            STOP
      ENDIF
   60 IF ((BONT.GE.BT1).AND.(BONT.LE.BT2)) THEN
        FILES(1,KCB)=SFFILES(KCB,2,1)
        FILES(2,KCB)=SFFILES(KCB,2,2)
        FILES(3,KCB)=SFFILES(KCB,3,1)
        FILES(4,KCB)=SFFILES(KCB,3,2)
        GOTO 63
          ELSE IF ((BONT.GT.BT2).AND.(BONT.LE.BT3)) THEN
          FILES(1,KCB)=SFFILES(KCB,2,2)
          FILES(2,KCB)=SFFILES(KCB,2,3)
          FILES(3,KCB)=SFFILES(KCB,3,2)
          FILES(4,KCB)=SFFILES(KCB,3,3)
          GOTO 63
            ELSE
            WRITE (*,64)
            STOP
      ENDIF
   63 DO 65 KF=1,4
        OPEN (KCB*100+KF,FILE=FILES(KF,KCB),STATUS='OLD')
   65 CONTINUE
```

```
      DO 66 KT=1,4
        DO 67 KFN=1,25
          READ (KCB*100+KT,75) (CR64(KFN,KT,KSL,KCB),KSL=1,5)
 67     CONTINUE
 66   CONTINUE
      DO 68 KF2=1,4
        CLOSE (KCB*100+KF2)
 68   CONTINUE
      DO 69 KFN=1,25
        FNINI=KFN
        FNS64(KFN)=(FNINI/5.0)*0.297584
        IF (FNS64(KFN).GT.FN) THEN
          DO 70 INT=1,4
            CALL INTERP(FNS64(KFN-1),FNS64(KFN),CR64(KFN-1,INT,2,KCB),
     +          CR64(KFN,INT,2,KCB),FN,CRARR(INT,1,KCB))
            CALL INTERP(FNS64(KFN-1),FNS64(KFN),CR64(KFN-1,INT,3,KCB),
     +          CR64(KFN,INT,3,KCB),FN,CRARR(INT,2,KCB))
            CALL INTERP(FNS64(KFN-1),FNS64(KFN),CR64(KFN-1,INT,4,KCB),
     +          CR64(KFN,INT,4,KCB),FN,CRARR(INT,3,KCB))
            CALL INTERP(FNS64(KFN-1),FNS64(KFN),CR64(KFN-1,INT,5,KCB),
     +          CR64(KFN,INT,5,KCB),FN,CRARR(INT,4,KCB))
 70       CONTINUE
          IF ((SLWL.GE.SL1).AND.(SLWL.LE.SL2)) THEN
            DO 71 INT2=1,4
          CALL INTERP(SL1,SL2,CRARR(INT2,1,KCB),
     +        CRARR(INT2,2,KCB),SLWL,CRARR2(INT2,KCB))
 71         CONTINUE
          ELSE IF ((SLWL.GT.SL2).AND.(SLWL.LE.SL3)) THEN
          DO 72 INT2=1,4
            CALL INTERP(SL2,SL3,CRARR(INT2,2,KCB),
     +          CRARR(INT2,3,KCB),SLWL,CRARR2(INT2,KCB))
 72       CONTINUE
            ELSE IF ((SLWL.GT.SL3).AND.(SLWL.LE.SL4)) THEN
            DO 73 INT2=1,4
              CALL INTERP(SL3,SL4,CRARR(INT2,3,KCB),
     +            CRARR(INT2,4,KCB),SLWL,CRARR2(INT2,KCB))
 73         CONTINUE
              ELSE
              WRITE (*,*) ' S/LWL RATIO IS OUT OF RANGE'
              STOP
          ENDIF
          IF ((BONT.GE.BT1).AND.(BONT.LE.BT2)) THEN
            CALL INTERP(BT1,BT2,CRARR2(1,KCB),CRARR2(2,KCB),
     +          BONT,CRARR3(1,KCB))
            CALL INTERP(BT1,BT2,CRARR2(3,KCB),CRARR2(4,KCB),
     +          BONT,CRARR3(2,KCB))
          ELSE
          CALL INTERP(BT2,BT3,CRARR2(1,KCB),CRARR2(2,KCB),
     +        BONT,CRARR3(1,KCB))
          CALL INTERP(BT2,BT3,CRARR2(3,KCB),CRARR2(4,KCB),
     +        BONT,CRARR3(2,KCB))
          ENDIF
          IF ((LD.GE.CIRCM(KCB,2)).AND.(LD.LE.CIRCM(KCB,3))) THEN
            CALL INTERP(CIRCM(KCB,2),CIRCM(KCB,3),CRARR3(1,KCB),
     +          CRARR3(2,KCB),LD,CRARR4(KCB))
          ELSE
          CALL INTERP(CIRCM(KCB,1),CIRCM(KCB,2),CRARR3(1,KCB),
     +        CRARR3(2,KCB),LD,CRARR4(KCB))
          ENDIF
          GOTO 58
        ENDIF
 69   CONTINUE
 58   CONTINUE
      CALL PARAB(CB1,CB2,CB3,CRARR4(1),CRARR4(2),CRARR4(3),CB,CR1)
      CR=CR1/1000.0
 75   FORMAT (5F7.3)
 64   FORMAT (' B/T RATIO IS OUT OF RANGE')
 62   FORMAT (' L/D RATIO IS OUT OF RANGE')
      RETURN
      END
C-----------------------------------------------------------------------
      SUBROUTINE TDCALC
      COMMON/TWO/ALFA,FV
      COMMON/FOUR/TD
      A1=7.0
      A2=11.0
      A3=16.0
      TD7=0.43803-0.92242*FV+0.81950*(FV**2.0)-0.32145*(FV**3.0)
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     ++0.04659*(FV**4.0)
      TD11=0.36479-0.68502*FV+0.69963*(FV**2.0)-0.34875*(FV**3.0)
     ++0.06700*(FV**4.0)
      TD16=0.41018-0.47956*FV+0.22567*(FV**2.0)-0.03129*(FV**3.0)
      IF ((ALFA.GE.7.0).AND.(ALFA.LT.11.0)) THEN
      CALL INTERP(A1,A2,TD7,TD11,ALFA,TD)
        ELSE IF ((ALFA.GE.11.0).AND.(ALFA.LE.16.0)) THEN
        CALL INTERP(A2,A3,TD11,TD16,ALFA,TD)
          ELSE
          WRITE (*,*) ' SHAFT ANGLE OUT OF RANGE'
          STOP
      ENDIF
      RETURN
      END
C-----------------------------------------------------------------------
      SUBROUTINE HOCALC
      REAL J,KT,KQ,KT1
      INTEGER Z
      CHARACTER *1 PRSER
      CHARACTER *11 KTFILE,KQFILE
      DIMENSION H0ARR(0:100),H0OPT(0:10)
      DIMENSION CNKT(39),SKT(39),TKT(39),UKT(39),VKT(39)
      DIMENSION CNKQ(47),SKQ(47),TKQ(47),UKQ(47),VKQ(47)
      COMMON/FOUR/TD
      COMMON/THREE/H0,DIAM,WT,BAR,Z,RTA,VS
      PI=3.14159
      SREV=0.2
      H0ARR(0)=0.0
      H0OPT(0)=0.0
      THRUST=((RTA/2.0)/(1.0-TD))
      WRITE (10,4005) THRUST
 4005 FORMAT (' THRUST PER SHAFT = ',F9.1,' N')
      RPS=SQRT(THRUST/(0.2*1025*(DIAM**4.0)))
      WRITE (10,4014) RPS
   44 WRITE (*,*) ' '
      WRITE (*,*) ' SELECT PROPELLER SERIES TO BE USED'
      WRITE (*,*) ' (W)AGENINGEN-B OR (G)AWN'
      READ (*,52) PRSER
   52 FORMAT (A)
      IF ((PRSER.EQ.'W').OR.(PRSER.EQ.'w')) THEN
      KTFILE='WAGENKT.DAT'
      KQFILE='WAGENKQ.DAT'
        ELSE IF ((PRSER.EQ.'G').OR.(PRSER.EQ.'g')) THEN
        KTFILE='GAWNKT.DAT'
        KQFILE='GAWNKQ.DAT'
          ELSE
          WRITE (*,*) ' I SPECIFICALLY ASKED FOR A "W" OR A "G"'
          GOTO 44
      ENDIF
      OPEN (5,FILE=KTFILE,STATUS='OLD')
      OPEN (6,FILE=KQFILE,STATUS='OLD')
      VA=VS*(1.0-WT)
      WRITE (10,4006) VA
 4006 FORMAT (' VA = ',F5.2,' m/s')
      DO 45 KKT=1,39
      READ (5,*) CNKT(KKT),SKT(KKT),TKT(KKT),UKT(KKT),VKT(KKT)
   45 CONTINUE
      DO 47 KKQ=1,47
      READ (6,*) CNKQ(KKQ),SKQ(KKQ),TKQ(KKQ),UKQ(KKQ),VKQ(KKQ)
   47 CONTINUE
      KH0=1
      KTRAP=0
      KOPT=1
   43 J=VA/(RPS*DIAM)
      KT1=THRUST/(1025*(RPS**2.0)*(DIAM**4.0))
      WRITE (10,4007) J,KT1
 4007 FORMAT (' J = ',F5.3,5X,' KT1 = ',F9.5)
      PD=1.0
   46 KT=0.0
      FKT=0.0
      DO 53 KKT=1,39
      KT=KT+(CNKT(KKT)*(J**SKT(KKT))*(PD**TKT(KKT))*(BAR**UKT(KKT))
     +     *(Z**VKT(KKT)))
      FKT=FKT+(CNKT(KKT)*(J**SKT(KKT))*TKT(KKT)*(PD**(TKT(KKT)-1.0))
     +     *(BAR**UKT(KKT))*(Z**VKT(KKT)))
   53 CONTINUE
      WRITE (10,4008) KT
 4008 FORMAT (' KT = ',F9.5)
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      DIFFKT=ABS(KT-KT1)
      WRITE (10,4009) DIFFKT
 4009 FORMAT (' DIFFKT = ',F9.5)
      IF (DIFFKT.GT.0.0001) THEN
      WRITE (10,4010) PD
      PD=PD-((KT-KT1)/FKT)
      WRITE (10,4010) PD
      GOTO 46
      ENDIF
 4010 FORMAT (' P/D = ',F7.4)
      KQ=0.0
      DO 54 KKQ=1,47
      KQ=KQ+(CNKQ(KKQ)*(J**SKQ(KKQ))*(PD**TKQ(KKQ))*(BAR**UKQ(KKQ))
     +    *(Z**VKQ(KKQ)))
   54 CONTINUE
      WRITE (10,4011) KQ
 4011 FORMAT (' KQ = ',F9.5)
      H0ARR(KH0)=(J*KT)/(2.0*PI*KQ)
      WRITE (10,4012) KH0,H0ARR(KH0)
 4012 FORMAT (' H0(',I2,') = ',F6.4)
      IF (KTRAP.EQ.1) THEN
      H0OPT(KOPT)=H0ARR(KH0)
      WRITE (10,4013) KOPT,H0OPT(KOPT)
      GOTO 48
      ENDIF
 4013 FORMAT (' H0OPT(',I1,') = ',F6.4)
      IF (H0ARR(KH0).LT.H0ARR(KH0-1)) THEN
      CALL QUADRA(H0ARR(KH0-2),H0ARR(KH0-1),H0ARR(KH0),SREV,
     +    RPS-SREV,RPSOPT)
      RPS=RPSOPT
      WRITE (10,4014) RPS
      KH0=KH0+1
      KTRAP=1
      GOTO 43
      ENDIF
 4014 FORMAT (' n = ',F6.3,' rps')
      RPS=RPS+SREV
      WRITE (10,4014) RPS
      KH0=KH0+1
      GOTO 43
   48 DIFFH0=ABS(H0OPT(KOPT)-H0OPT(KOPT-1))
      WRITE (10,4015) DIFFH0
 4015 FORMAT (' DIFFH0 = ',F7.5)
      IF (DIFFH0.GT.0.0001) THEN
      RPS=RPS-SREV
      WRITE (10,4014) RPS
      SREV=SREV/3.0
      WRITE (10,4016) SREV
      KTRAP=0
      KH0=1
      KOPT=KOPT+1
      GOTO 43
        ELSE
        H0=H0OPT(KOPT)
      ENDIF
 4016 FORMAT (' STEP = ',F5.3,' rps')
      CLOSE (5)
      CLOSE (6)
      RPM=RPS*60.0
      WRITE (*,*) ' '
      WRITE (10,4010) PD
      WRITE (*,50) H0,RPM
      WRITE (10,50) H0,RPM
   50 FORMAT (' OPTIMUM OPEN WATER EFF. = ',F5.3,5X,'AT ',F6.1,' rpm')
      RETURN
      END
C-----------------------------------------------------------------------
      SUBROUTINE INTERP(XA,XB,YA,YB,XM,YM)
      DX=XB-XA
      DY=YB-YA
      HX=XM-XA
      RX=HX/DX
      YM=YA+(RX*DY)
      RETURN
      END
C-----------------------------------------------------------------------
      SUBROUTINE PARAB(X1,X2,X3,Y1,Y2,Y3,X,Y)
      QUAD(X)=A+(B*X)+(C*(X**2.0))
```

```
      D=(X2*(X3**2.0)-X3*(X2**2.0))-X1*(X3**2.0-X2**2.0)
     ++(X1**2.0)*(X3-X2)
      A=(Y1*(X2*(X3**2.0)-X3*(X2**2.0))-X1*(Y2*(X3**2.0)-Y3*(X2**2.0))
     ++(X1**2.0)*(Y2*X3-Y3*X2))/D
      B=((Y2*(X3**2.0)-Y3*(X2**2.0))-Y1*(X3**2.0-X2**2.0)
     ++(X1**2.0)*(Y3-Y2))/D
      C=(X2*Y3-X3*Y2-X1*(Y3-Y2)+Y1*(X3-X2))/D
      Y=QUAD(X)
      RETURN
      END
C-----------------------------------------------------------------------
      SUBROUTINE QUADRA(Y1,Y2,Y3,S,X2,XR)
      SM=S*(Y1-Y3)/(2.0*(Y1-2.0*Y2+Y3))
      XR=X2+SM
      RETURN
      END
```

```
 *************************************************

  PRELIMINARY ESTIMATION OF REQUIRED INSTALLED
  POWER FOR HIGH-SPEED CATAMARAN FERRIES

 *************************************************

  INPUT VESSEL'S MAIN DIMENSIONS IN THE FOLLOWING
  ORDER: LWL, BH, T, S
   68.62000       5.440000       3.400000       14.41000

  INPUT SPEED FOR WHICH TO PERFORM CALCULATIONS (KN)
   36.00000

  SELECT SERIES TO BE USED FOR RESISTANCE CALCULATION
  SOUTHAMPTON EXTENDED (N)PL OR (S)ERIES-64
N
 CR =     0.2862E-02     CF =     0.1518E-02     CT =      0.438
0E-02
 CS =  2.650     WS =   989.4 m^2
  SELECT ALLOWANCE FOR APPENDAGES IN % (10-25)
   10.00000
 RT =  838.2 kN       PE = 15525.2 kW

  IF WATERJETS ARE INSTALLED,  THERE IS NO APPENDAGE
  DRAG. IN THIS CASE, TOTAL RESISTANCE AND EFFECTIVE
  HORSEPOWER ARE:
 RT =  762.0 kN       PE = 14113.8 kW

  INPUT BLADE AREA RATIO, SHAFT ANGLE (DEG)
  AND NUMBER OF BLADES
   1.000000       9.000000              5

 HULL EFF. = 0.898     REL. ROTATIVE EFF. = 0.956

  SELECT PROPELLER SERIES TO BE USED
  (W)AGENINGEN-B OR (G)AWN
W

 OPTIMUM OPEN WATER EFF. = 0.660     AT  671.8 rpm

 QUASI PROPULSIVE COEFFICIENT = 0.566

 DHP = 27409.7 kW     BHP = 29131.3 kW

  IF WATERJETS ARE INSTALLED, THE QUASI PROPULSIVE
  COEFFICIENT IS: 0.682
  AND THE REQUIRED INSTALLED POWER IS:
 DHP = 20700.3 kW     BHP = 22000.5 kW

  DO YOU WANT TO PERFORM CALCULATIONS FOR A
```

CATPOWER - Example I/O

```
  DIFFERENT SPEED? (Y/N)
N

  DO YOU WANT TO PERFORM CALCULATIONS FOR
  ANOTHER VESSEL? (Y/N)
N
```

```
      PROGRAM MASS
      CHARACTER *1 YESNO,VTYPE,ETYPE,PTYPE
      REAL MARGIN,LB1,LB2,LB3
      REAL L,L11,L12,L13,L21,L22,L23,L31,L32,L33,L1,L2,L3
      REAL LB,LB11,LB12,LB13,LB21,LB22,LB23,LB31,LB32,LB33
      WRITE (*,*) ' '
      WRITE (*,*) '**************************************************'
      WRITE (*,*) ' PRELIMINARY MASS ESTIMATION FOR'
      WRITE (*,*) ' HIGH-SPEED FERRIES'
      WRITE (*,*) '**************************************************'
  600 WRITE (*,*) ' '
      WRITE (*,*) ' INPUT VESSEL TYPE (M/C).'
      READ (*,630) VTYPE
      IF ((VTYPE.NE.'M').AND.(VTYPE.NE.'m').AND.(VTYPE.NE.'C').AND.
     +(VTYPE.NE.'c')) THEN
      WRITE (*,*) ' I SPECIFICALLY ASKED FOR AN "M" OR A "C".'
      GOTO 600
      ELSE
        CONTINUE
      ENDIF
  620 WRITE (*,*) ' '
      WRITE (*,*) ' INPUT MAIN ENGINE SPECIFICATION.'
      WRITE (*,*) ' D=DIESELS  T=TURBINES  C=CODAG'
      READ (*,630) ETYPE
      IF ((ETYPE.NE.'D').AND.(ETYPE.NE.'d').AND.(ETYPE.NE.'T').AND.
     +(ETYPE.NE.'t').AND.(ETYPE.NE.'C').AND.(ETYPE.NE.'c')) THEN
      WRITE (*,*) ' I SPECIFICALLY ASKED FOR A "D" A "T" OR A "C".'
      GOTO 620
      ELSE
        CONTINUE
      ENDIF
  621 WRITE (*,*) ' '
      WRITE (*,*) ' INPUT PROPULSORS (P=PROPELLERS  J=WATERJETS).'
      READ (*,630) PTYPE
      IF ((PTYPE.NE.'P').AND.(PTYPE.NE.'p').AND.(PTYPE.NE.'J').AND.
     +(PTYPE.NE.'j')) THEN
      WRITE (*,*) ' I SPECIFICALLY ASKED FOR A "P" OR A "J".'
      GOTO 621
      ELSE
        CONTINUE
      ENDIF
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT INSTALLED POWER (kW).'
      READ (*,*) PB
      IF ((ETYPE.EQ.'D').OR.(ETYPE.EQ.'d')) THEN
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT ENGINE SPEED (rpm).'
      READ (*,*) RPM
      PSRATIO=PB/RPM
      WME=5.86*(PSRATIO**0.89)
      ELSE IF ((ETYPE.EQ.'T').OR.(ETYPE.EQ.'t')) THEN
        WGT=0.55*(PB**0.9)/1000.0
        WME=5.0+(0.6*((PB/1000.0)**0.9))
        ELSE
          WRITE (*,*) ' '
          WRITE (*,*) ' INPUT TOTAL INSTALLED POWER OF DIESELS (kW)'
          WRITE (*,*) ' AND THEIR ENGINE SPEED (rpm).'
          READ (*,*) PBD,RPM
          PBGT=PB-PBD
          PSRATIO=PBD/RPM
          WD=5.86*(PSRATIO**0.89)
          WGT=0.55*(PBGT**0.9)/1000.0
          WGTM=5.0+(0.6*((PBGT/1000.0)**0.9))
          WME=WD+WGTM
      ENDIF
      IF ((PTYPE.EQ.'P').OR.(PTYPE.EQ.'p')) THEN
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT THE VESSEL''S DRAUGHT (m).'
      READ (*,*) T
      DIAM=0.6*T
      WP=1.5*DIAM
      ELSE
        WRITE (*,*) ' '
        WRITE (*,*) ' INPUT NUMBERS OF STEERABLE AND BOOSTER JETS.'
        READ (*,*) NSWJ,NBWJ
        WRITE (*,*) ' '
        WRITE (*,*) ' INPUT POWER ABSORBED BY STEERABLE JETS (kW).'
        READ (*,*) PSWJ
```

```
      PBWJ=PB-PSWJ
      BWJ=PBWJ/NBWJ
      SWJ=PSWJ/NSWJ
      DSWJ=22.3*(SWJ**0.44)
      DBWJ=22.3*(BWJ**0.44)
      WSWJ=1.1*((-2E-7*(DSWJ**3.0))+(0.0063*(DSWJ**2.0))
     +        -(2.1*DSWJ)+200)/1000.0
      WBWJ=0.75*((-2E-7*(DBWJ**3.0))+(0.0063*(DBWJ**2.0))
     +        -(2.1*DBWJ)+200)/1000.0
      WP=WSWJ+WBWJ
      ENDIF
      WGB=((0.428*PB)+77)/1000.0
      WMM=WME+WP+WGB
      IF (((ETYPE.EQ.'D').OR.(ETYPE.EQ.'d')).AND.
     +((PTYPE.EQ.'P').OR.(PTYPE.EQ.'p'))) THEN
      FACTOR=1.4
      ELSE IF (((ETYPE.EQ.'D').OR.(ETYPE.EQ.'d')).AND.
     +     ((PTYPE.EQ.'J').OR.(PTYPE.EQ.'j'))) THEN
        FACTOR=1.6
        ELSE IF (((ETYPE.EQ.'T').OR.(ETYPE.EQ.'t')).AND.
     +       ((PTYPE.EQ.'P').OR.(PTYPE.EQ.'p'))) THEN
          FACTOR=4.5
          ELSE IF (((ETYPE.EQ.'T').OR.(ETYPE.EQ.'t')).AND.
     +         ((PTYPE.EQ.'J').OR.(PTYPE.EQ.'j'))) THEN
            FACTOR=5.0
            ELSE IF (((ETYPE.EQ.'C').OR.(ETYPE.EQ.'c')).AND.
     +           ((PTYPE.EQ.'P').OR.(PTYPE.EQ.'p'))) THEN
          FACTOR=(1.4+((4.5-1.4)*(PBGT/PB)))
          ELSE
            FACTOR=(1.6+((5.0-1.6)*(PBGT/PB)))
      ENDIF
      WM=WMM*FACTOR
      WRITE (*,*) ' '
      WRITE (*,*) ' MACHINERY MASS'
      WRITE (*,*) ' --------------'
      WRITE (*,*) '                                t'
      WRITE (*,608) WME
      WRITE (*,609) WP
      WRITE (*,610) WGB
      WRITE (*,611) WM
  608 FORMAT ('  MAIN ENGINES:              ',F5.1)
  609 FORMAT ('  PROPULSORS:                ',F5.1)
  610 FORMAT ('  GEARBOXES:                 ',F5.1)
  611 FORMAT ('  TOTAL MACHINERY MASS:      ',F5.1)
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT TOTAL AREA FOR USE BY PASSENGERS (m2).'
      READ (*,*) AP
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT THE VESSEL''S LENGTH, BEAM (DEMIHULL BEAM'
      WRITE (*,*) ' FOR CATAMARANS) AND DEPTH (m).'
      READ (*,*) L,B,D
      WBA=0.085*AP
      IF ((VTYPE.EQ.'M').OR.(VTYPE.EQ.'m')) THEN
      WOR=1.5*((L*B*D)/100.0)
      ELSE
        WOR=1.5*((L*2.0*B*D)/100.0)
      ENDIF
      WO=WBA+WOR
      WRITE (*,*) ' '
      WRITE (*,*) ' OUTFIT MASS'
      WRITE (*,*) ' -----------'
      WRITE (*,*) '                                           t'
      WRITE (*,612) WBA
      WRITE (*,613) WOR
      WRITE (*,615) WO
  612 FORMAT ('  BASIC ACCOMODATION MASS              ',F6.1)
  613 FORMAT ('  REMAINING OUTFIT MASS                ',F6.1)
  615 FORMAT ('  TOTAL                                ',F6.1)
      IF ((VTYPE.EQ.'C').OR.(VTYPE.EQ.'c')) THEN
      GOTO 622
      ENDIF
      L11=45
      L12=50
      L13=55
      L21=95
      L22=100
      L23=105
      L31=145
```

```
      L32=150
      L33=155
      LB11=4.58
      LB12=5.65
      LB13=6.84
      LB21=5.99
      LB22=6.64
      LB23=7.32
      LB31=6.29
      LB32=6.73
      LB33=7.18
      CALL PARAB(L11,L21,L31,LB11,LB21,LB31,L,LB1)
      CALL PARAB(L12,L22,L32,LB12,LB22,LB32,L,LB2)
      CALL PARAB(L13,L23,L33,LB13,LB23,LB33,L,LB3)
      LB=L/B
      WH1=(0.0658*(L**2.0))-(4.92*L)+200
      WH2=(0.0590*(L**2.0))-(3.29*L)+150
      WH3=(0.0642*(L**2.0))-(3.72*L)+160
      CALL PARAB(LB1,LB2,LB3,WH1,WH2,WH3,LB,WH)
      GOTO 624
622   WRITE (*,*) ' '
      WRITE (*,*) ' INPUT VESSEL''S HULL SEPARATION (m).'
      READ (*,*) S
      L1=50
      L2=75
      L3=100
      SL11=0.196
      SL12=0.224
      SL13=0.258
      SL21=0.218
      SL22=0.239
      SL23=0.260
      SL31=0.209
      SL32=0.222
      SL33=0.238
      SL=S/L
      CALL PARAB(L1,L2,L3,SL11,SL21,SL31,L,SL1)
      CALL PARAB(L1,L2,L3,SL12,SL22,SL32,L,SL2)
      CALL PARAB(L1,L2,L3,SL13,SL23,SL33,L,SL3)
      WH1=(0.0336*(L**2.0))+(08.16*L)-240
      WH2=(0.0120*(L**2.0))+(11.58*L)-335
      WH3=(0.0280*(L**2.0))+(09.34*L)-230
      CALL PARAB(SL1,SL2,SL3,WH1,WH2,WH3,SL,WH)
624   WRITE (*,*) ' '
      WRITE (*,*) ' HULL MASS'
      WRITE (*,*) ' ---------'
      WRITE (*,*) '                                    t'
      WRITE (*,625) WH
625   FORMAT ('  TOTAL HULL MASS:          ',F6.1)
      DISP=DWT+WO+WM+WH
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT PASSENGER AND CAR CAPACITY AND CREW NUMBER.'
      READ (*,*) NP,NV,NC
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT CROSSING DISTANCE (nm), SERVICE SPEED (kn)'
      WRITE (*,*) ' AND REQUIRED MARGIN FOR BALLAST AND/OR CARGO (t).'
      READ (*,*) CD,VS,MARGIN
      NRT=18.0/(2.0*CD/VS)
      IF ((ETYPE.EQ.'C').OR.(ETYPE.EQ.'c')) THEN
      GOTO 635
      ENDIF
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT SERVICE POWER AND SPECIFIC FUEL CONSUMPTION'
      WRITE (*,*) ' OF MAIN ENGINES (kW AND g/kWh RESPECTIVELY).'
      READ (*,*) PS,SFC
      FUEL=NRT*((PS*SFC*(2.0*CD/VS))*1.09*1.1)/1000000.0
      GOTO 636
635   WRITE (*,*) ' '
      WRITE (*,*) ' INPUT SERVICE POWER OF DIESELS'
      WRITE (*,*) ' AND GAS TURBINES (kW).'
      READ (*,*) PSD,PSGT
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT SPECIFIC FUEL CONSUPMTION OF DIESELS'
      WRITE (*,*) ' AND GAS TURBINES (g/kWh).'
      READ (*,*) SFCD,SFCGT
      FUEL=NRT*(((PSD*SFCD*(2.0*CD/VS))*1.09*1.1)
     ++((PSGT*SFCGT*(2.0*CD/VS))*1.09*1.1))/1000000.0
636   FWPROV=0.03*NP
```

```
      PAX=NP*0.105
      CREW=NC*0.135
      CARS=NV*1.0
      DWT=FUEL+FWPROV+PAX+CREW+CARS+MARGIN
      WRITE (*,*) ' '
      WRITE (*,*) ' DEADWEIGHT ANALYSIS'
      WRITE (*,*) ' -------------------'
      WRITE (*,*) '                                           t'
      WRITE (*,601) FUEL
      WRITE (*,602) FWPROV
      WRITE (*,603) CREW
      WRITE (*,604) PAX
      WRITE (*,605) CARS
      WRITE (*,606) MARGIN
      WRITE (*,607) DWT
  601 FORMAT ('  FUEL & LUBRICANT                   ',F6.1)
  602 FORMAT ('  WATER & PROVISIONS                 ',F6.1)
  603 FORMAT ('  CREW & EFFECTS                     ',F6.1)
  604 FORMAT ('  PASSENGERS & LUGGAGE               ',F6.1)
  605 FORMAT ('  VEHICLES                           ',F6.1)
  606 FORMAT ('  MARGIN FOR CARGO AND/OR BALLAST    ',F6.1)
  607 FORMAT ('  TOTAL                              ',F6.1)
      WRITE (*,*) ' '
      WRITE (*,*) ' THE VESSEL''S TOTAL DISPLACEMENT IS'
      WRITE (*,626) DISP
  626 FORMAT (2X,F6.1,1X,'t')
  627 WRITE (*,*) ' '
      WRITE (*,*) ' DO YOU WANT TO PERFORM CALCULATIONS'
      WRITE (*,*) ' FOR ANOTHER VESSEL (Y/N)?'
      READ (*,630) YESNO
      IF ((YESNO.EQ.'Y').OR.(YESNO.EQ.'y')) THEN
      GOTO 600
      ELSE IF ((YESNO.EQ.'N').OR.(YESNO.EQ.'n')) THEN
        GOTO 628
        ELSE
          WRITE (*,*) ' '
          WRITE (*,*) ' I SPECIFICALLY ASKED FOR A "Y" OR AN "N".'
          GOTO 627
      ENDIF
  630 FORMAT (A)
  628 STOP
      END
C-----------------------------------------------------------------------
      SUBROUTINE PARAB(X1,X2,X3,Y1,Y2,Y3,X,Y)
      QUAD(X)=A+(B*X)+(C*(X**2.0))
      D=(X2*(X3**2.0)-X3*(X2**2.0))-X1*(X3**2.0-X2**2.0)
     ++(X1**2.0)*(X3-X2)
      A=(Y1*(X2*(X3**2.0)-X3*(X2**2.0))-X1*(Y2*(X3**2.0)-Y3*(X2**2.0))
     ++(X1**2.0)*(Y2*X3-Y3*X2))/D
      B=((Y2*(X3**2.0)-Y3*(X2**2.0))-Y1*(X3**2.0-X2**2.0)
     ++(X1**2.0)*(Y3-Y2))/D
      C=(X2*Y3-X3*Y2-X1*(Y3-Y2)+Y1*(X3-X2))/D
      Y=QUAD(X)
      RETURN
      END
```

COST 98

```
      PROGRAM COST
      CHARACTER *1 YESNO,YN,ETYPE,VTYPE
      REAL LWL,LPRICE
      WRITE (*,*) ' '
      WRITE (*,*) ' ************************************************'
      WRITE (*,*) ' PRELIMINARY COST ESTIMATION '
      WRITE (*,*) ' FOR HIGH-SPEED FERRIES'
      WRITE (*,*) ' ************************************************'
  514 WRITE (*,*) ' '
      WRITE (*,*) ' INPUT WATERLINE LENGTH (m).'
      READ (*,*) LWL
  660 WRITE (*,*) ' '
      WRITE (*,*) ' INPUT VESSEL TYPE (M/C).'
      READ (*,516) VTYPE
      IF ((VTYPE.NE.'M').AND.(VTYPE.NE.'m').AND.(VTYPE.NE.'C').AND.
     +(VTYPE.NE.'c')) THEN
      WRITE (*,*) ' I SPECIFICALLY ASKED FOR AN "M" OR A "C".'
      GOTO 660
      ELSE
        CONTINUE
      ENDIF
  620 WRITE (*,*) ' '
      WRITE (*,*) ' INPUT MAIN ENGINE SPECIFICATION.'
      WRITE (*,*) ' D=DIESELS  T=TURBINES  C=CODAG'
      READ (*,516) ETYPE
      IF ((ETYPE.NE.'D').AND.(ETYPE.NE.'d').AND.(ETYPE.NE.'T').AND.
     +(ETYPE.NE.'t').AND.(ETYPE.NE.'C').AND.(ETYPE.NE.'c')) THEN
      WRITE (*,*) ' I SPECIFICALLY ASKED FOR A "D" A "T" OR A "C".'
      GOTO 620
      ELSE
        CONTINUE
      ENDIF
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT TOTAL PASSENGER AREA (m2).'
      READ (*,*) AP
      WACC=0.11*AP
      WO=WACC*1.4
      IF ((VTYPE.EQ.'C').OR.(VTYPE.EQ.'c')) THEN
      WH=(0.012*(LWL**2.0))+(11.58*LWL)-335
      ELSE
        WH=(0.059*(LWL**2.0))-(3.2892*LWL)+148
      ENDIF
      CO=(WO*18.0)*1.8/1000.0
      CH=WH*22.0/1000.0
C     WRITE (*,*) ' '
C     WRITE (*,*) ' INPUT THE MAIN OPERATIONAL PARAMETERS IN THE'
C     WRITE (*,*) ' FOLLOWING ORDER: SERVICE SPEED (kn), CROSSING'
C     WRITE (*,*) ' DISTANCE (n.m.), REDUCED SPEED (kn), DISTANCE'
C     WRITE (*,*) ' AT REDUCED SPEED (n.m.), MANOEUVRING TIME AT'
C     WRITE (*,*) ' EACH PORT AND TURNAROUND TIME AT EACH PORT (min).'
C     READ (*,*) VS,DIST,VR,DR,TM,TT
C     WRITE (*,*) ' '
C     WRITE (*,*) ' INPUT OPERATING DAYS PER YEAR.'
C     READ (*,*) DAYS
      VS=36.0
      DIST=40.0
      VR=12.0
      DR=4.0
      TM=10.0
      TT=30.0
      DAYS=330.0
      TR=DR/VR
      DF=DIST-DR
      TF=DF/VS
      TMH=TM/60.0
      TTH=TT/60.0
      TRT=(TF+TR+(2.0*TMH)+TTH)*2.0
      NRT=18.0/TRT
      IF ((ETYPE.EQ.'C').OR.(ETYPE.EQ.'c')) THEN
      GOTO 635
      ENDIF
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT ENGINE POWER AT FULL SPEED, REDUCED SPEED AND'
C     WRITE (*,*) ' MANOEUVRING (kW) AND THEN THE CORRESPONDING'
C     WRITE (*,*) ' SPECIFIC FUEL CONSUMPTIONS (g/kWh).'
C     READ (*,*) PF,PR,PM,SFCF,SFCR,SFCM
      READ (*,*) PF
      PR=PF/15.0
```

```
      PM=500.0
      IF ((ETYPE.EQ.'D').OR.(ETYPE.EQ.'d')) THEN
      SFCF=210.0
      SFCR=220.0
      SFCM=220.0
      ELSE
        SFCF=220.0
        SFCR=260.0
        SFCM=400.0
      ENDIF
      FCF=2.0*PF*SFCF*TF
      FCR=2.0*PR*SFCR*TR
      FCM=2.0*PM*SFCM*TMH*2.0
      GOTO 636
  635 WRITE (*,*) ' '
C     WRITE (*,*) ' INPUT POWER OF DIESELS AND GAS TURBINES AT FULL'
C     WRITE (*,*) ' SPEED, REDUCED SPEED AND MANOEUVRING (kW).'
C     READ (*,*) PSD,PSGT,PRD,PRGT,PMD,PMGT
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT ENGINE POWER AT FULL SPEED, REDUCED SPEED AND'
C     WRITE (*,*) ' MANOEUVRING (kW).'
C     READ (*,*) PF,PR,PM
      READ (*,*) PF
      PR=PF/15.0
      PM=500.0
      PSD=PF*0.35
      PRD=PR*0.35
      PMD=PM*0.35
      PSGT=PF-PSD
      PRGT=PR-PRD
      PMGT=PM-PMD
C     WRITE (*,*) ' '
C     WRITE (*,*) ' INPUT SPECIFIC FUEL CONSUMPTION OF DIESELS'
C     WRITE (*,*) ' AND GAS TURBINES AT FULL SPEED, REDUCED SPEED'
C     WRITE (*,*) ' AND MANOEUVRING (g/kWh).'
C     READ (*,*) SFCD,SFCGT,SFCRD,SFCRGT,SFCMD,SFCMGT
      SFCD=210.0
      SFCGT=220.0
      SFCRD=220.0
      SFCRGT=260.0
      SFCMD=220.0
      SFCMGT=400.0
      FCF=2.0*((PSD*SFCD)+(PSGT*SFCGT))*TF
      FCR=2.0*((PRD*SFCRD)+(PRGT*SFCRGT))*TR
      FCM=2.0*((PMD*SFCMD)+(PMGT*SFCMGT))*TMH*2.0
  636 FCRT=(FCF+FCR+FCM)/1000.0
      FCD=FCRT*NRT*1.06
      FCL=FCRT*NRT*0.03
  701 WRITE (*,*) ' '
      WRITE (*,*) ' INPUT POWER MARGIN (%).'
      READ (*,*) RAW
      RAW=RAW/100.0
      PB=PF*(1.0+RAW)
      IF ((ETYPE.EQ.'D').OR.(ETYPE.EQ.'d')) THEN
      CME=0.253*PB
      ELSE IF ((ETYPE.EQ.'T').OR.(ETYPE.EQ.'t')) THEN
        CME=((2E-10*(PB**3.0))-(1E-5*(PB**2.0))+(0.411*PB))
        ELSE
C         WRITE (*,*) ' '
C         WRITE (*,*) ' INPUT TOTAL INSTALLED POWER OF DIESELS (kW).'
C         READ (*,*) PBD
C         PBGT=PB-PBD
          PBD=PB*0.35
          PBGT=PB-PBD
          CDE=0.253*PBD
          CGT=((2E-10*(PBGT**3.0))-(1E-5*(PBGT**2.0))+(0.411*PBGT))
          CME=CDE+CGT
          ENDIF
      CWJ=3.067*(PB**0.61)
      CGB=(-3E-7*(PB**2.0))+(0.0237*PB)
      CM=(CME+CWJ+CGB)/1000.0
      BC=(CO+CH+CM)*1.12
      WRITE (*,*) ' '
      WRITE (*,*) ' BUILDING COST'
      WRITE (*,*) ' -------------                        M $US'
      WRITE (*,*) ' '
      WRITE (*,650) CO
      WRITE (*,651) CH
```

```
      WRITE (*,652) CM
      WRITE (*,653) BC
  650 FORMAT ('  OUTFITTING COST:                    ',F5.1)
  651 FORMAT ('  HULL COST:                          ',F5.1)
  652 FORMAT ('  MACHINERY COST:                     ',F5.1)
  653 FORMAT ('  BUILDING COST (INCL. 12% MARGIN): ',F5.1)
C     WRITE (*,*) ' '
C     WRITE (*,*) ' INPUT REQUIRED RETURN ON CAPITAL (ANNUAL, % OF'
C     WRITE (*,*) ' BUILDING COST) AND ECONOMIC LIFE (YEARS).'
C     READ (*,*) ROC,EY
      ROC=10.0
      EY=10.0
      ROC=ROC/100.0
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT FUEL PRICE ($/t).'
      READ (*,*) FPRICE
      LPRICE=FPRICE*10.0
      FCOSTD=(FCD/1000.0)*FPRICE
      FCOSTL=(FCL/1000.0)*LPRICE
      TDOC=FCOSTD+FCOSTL
      TAOC=(TDOC*DAYS)/1000.0
      CRF=(ROC*((1.0+ROC)**EY))/(((1.0+ROC)**EY)-1.0)
      CCOST=(CRF*BC)*1000.0
      TACOST=TAOC+CCOST
      WRITE (*,*) ' '
      WRITE (*,*) ' TOTAL RUNNING COSTS (ANNUAL)'
      WRITE (*,*) ' ----------------------------'
      WRITE (*,*) '                              K US$'
      WRITE (*,508) TAOC
      WRITE (*,512) CCOST
      WRITE (*,*) ' '
      WRITE (*,513) TACOST
  508 FORMAT ('  FUEL COST                   ',F8.0)
  512 FORMAT ('  CAPITAL COST                ',F8.0)
  513 FORMAT ('  TOTAL                       ',F8.0)
  700 WRITE (*,*) ' '
      WRITE (*,*) ' DO YOU WANT TO PERFORM CALCULATIONS FOR'
      WRITE (*,*) ' ANOTHER SCENARIO? (Y/N)'
      READ (*,516) YN
      IF ((YN.EQ.'Y').OR.(YN.EQ.'y')) THEN
      GOTO 701
      ELSE IF ((YN.NE.'N').AND.(YN.NE.'n')) THEN
        WRITE (*,*) ' I SPECIFICALLY ASKED FOR AN "Y" OR AN "N"'
        GOTO 700
      ENDIF
  515 WRITE (*,*) ' '
      WRITE (*,*) ' DO YOU WANT TO PERFORM CALCULATIONS FOR'
      WRITE (*,*) ' ANOTHER VESSEL? (Y/N)'
      READ (*,516) YESNO
      IF ((YESNO.EQ.'Y').OR.(YESNO.EQ.'y')) THEN
      GOTO 514
      ELSE IF ((YESNO.NE.'N').AND.(YESNO.NE.'n')) THEN
        WRITE (*,*) ' I SPECIFICALLY ASKED FOR AN "Y" OR AN "N"'
        GOTO 515
      ENDIF
  516 FORMAT (A)
      STOP
      END
```

```
      PROGRAM COST
      CHARACTER *1 YESNO,YN,ETYPE,VTYPE
      REAL ICOST,MCOSTD,MCOSTY,MCOSTH,LWL,LPRICE
      WRITE (*,*) ' '
      WRITE (*,*) ' **************************************************'
      WRITE (*,*) ' PRELIMINARY COST ESTIMATION '
      WRITE (*,*) ' FOR HIGH-SPEED FERRIES'
      WRITE (*,*) ' **************************************************'
  514 WRITE (*,*) ' '
      WRITE (*,*) ' INPUT NUMBER OF PASSENGERS, NUMBER OF CARS'
      WRITE (*,*) ' AND SERVICE SPEED IN KNOTS.'
      READ (*,*) NP,NV,VS
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT WATERLINE LENGTH (m).'
      READ (*,*) LWL
  660 WRITE (*,*) ' '
      WRITE (*,*) ' INPUT VESSEL TYPE (M/C).'
      READ (*,516) VTYPE
      IF ((VTYPE.NE.'M').AND.(VTYPE.NE.'m').AND.(VTYPE.NE.'C').AND.
     +(VTYPE.NE.'c')) THEN
      WRITE (*,*) ' I SPECIFICALLY ASKED FOR AN "M" OR A "C".'
      GOTO 660
      ELSE
        CONTINUE
      ENDIF
  620 WRITE (*,*) ' '
      WRITE (*,*) ' INPUT MAIN ENGINE SPECIFICATION.'
      WRITE (*,*) ' D=DIESELS  T=TURBINES  C=CODAG'
      READ (*,516) ETYPE
      IF ((ETYPE.NE.'D').AND.(ETYPE.NE.'d').AND.(ETYPE.NE.'T').AND.
     +(ETYPE.NE.'t').AND.(ETYPE.NE.'C').AND.(ETYPE.NE.'c')) THEN
      WRITE (*,*) ' I SPECIFICALLY ASKED FOR A "D" A "T" OR A "C".'
      GOTO 620
      ELSE
        CONTINUE
      ENDIF
  701 WRITE (*,*) ' '
      WRITE (*,*) ' INPUT INSTALLED POWER (kW).'
      READ (*,*) PB
      IF ((ETYPE.EQ.'D').OR.(ETYPE.EQ.'d')) THEN
      CME=0.253*PB
      ELSE IF ((ETYPE.EQ.'T').OR.(ETYPE.EQ.'t')) THEN
        CME=((2E-10*(PB**3.0))-(1E-5*(PB**2.0))+(0.411*PB))
        ELSE
          WRITE (*,*) ' '
          WRITE (*,*) ' INPUT TOTAL INSTALLED POWER OF DIESELS (kW).'
          READ (*,*) PBD
          PBGT=PB-PBD
          CDE=0.253*PBD
          CGT=((2E-10*(PBGT**3.0))-(1E-5*(PBGT**2.0))+(0.411*PBGT))
          CME=CDE+CGT
      ENDIF
      CWJ=3.067*(PB**0.61)
      CGB=(-3E-7*(PB**2.0))+(0.0237*PB)
      WRITE (*,*) ' '
      WRITE (*,*) ' INPUT TOTAL PASSENGER AREA (m2).'
      READ (*,*) AP
      WACC=0.11*AP
      WO=WACC*1.4
      IF ((VTYPE.EQ.'C').OR.(VTYPE.EQ.'c')) THEN
      WH=(0.012*(LWL**2.0))+(11.58*LWL)-335
      ELSE
        WH=(0.059*(LWL**2.0))-(3.2892*LWL)+148
      ENDIF
      CO=((WO*18.0)*1.8)/1000.0
      CH=WH*22.0/1000.0
      CME=CME/1000.0
      BC=(CO+CH+CME)*1.12
      WRITE (*,*) ' '
      WRITE (*,*) ' BUILDING COST'
      WRITE (*,*) ' -------------                           M $US'
      WRITE (*,*) ' '
      WRITE (*,650) CO
      WRITE (*,651) CH
      WRITE (*,652) CME
      WRITE (*,653) BC
  650 FORMAT ('  OUTFITTING COST:                    ',F5.1)
  651 FORMAT ('  HULL COST:                          ',F5.1)
```

```
652 FORMAT ('  MACHINERY COST:                         ',F5.1)
653 FORMAT ('  BUILDING COST (INCL. 12% MARGIN): ',F5.1)
    WRITE (*,*) ' '
    WRITE (*,*) ' INPUT THE MAIN OPERATIONAL PARAMETERS IN THE'
    WRITE (*,*) ' FOLLOWING ORDER: CROSSING DISTANCE (n.m.), REDUCED'
    WRITE (*,*) ' SPEED (kn), DISTANCE AT REDUCED SPEED (n.m.),'
    WRITE (*,*) ' MANOEUVRING TIME AT EACH PORT AND TURNAROUND TIME'
    WRITE (*,*) ' AT EACH PORT (min).'
    READ (*,*) DIST,VR,DR,TM,TT
    WRITE (*,*) ' '
    WRITE (*,*) ' INPUT GROSS TONNAGE AND OPERATING DAYS PER YEAR.'
    READ (*,*) GRT,DAYS
    WRITE (*,*) ' '
    WRITE (*,*) ' INPUT CREW NUMBER AND AVERAGE WAGE (US$/YEAR).'
    READ (*,*) NC,WAGE
    WRITE (*,*) ' '
    WRITE (*,*) ' INPUT BASIC INSURANCE RATE (% OF BUILDING COST),'
    WRITE (*,*) ' REQUIRED RETURN ON CAPITAL (ANNUAL, % OF'
    WRITE (*,*) ' BUILDING COST) AND ECONOMIC LIFE (YEARS).'
    READ (*,*) BINS,ROC,EY
    TR=DR/VR
    DF=DIST-DR
    TF=DF/VS
    TMH=TM/60.0
    TTH=TT/60.0
    TRT=(TF+TR+(2.0*TMH)+TTH)*2.0
    NRT=18.0/TRT
    IF ((ETYPE.EQ.'C').OR.(ETYPE.EQ.'c')) THEN
    GOTO 635
    ENDIF
    WRITE (*,*) ' '
    WRITE (*,*) ' INPUT ENGINE POWER AT FULL SPEED, REDUCED SPEED AND'
    WRITE (*,*) ' MANOEUVRING (kW) AND THEN THE CORRESPONDING'
    WRITE (*,*) ' SPECIFIC FUEL CONSUMPTIONS (g/kWh).'
    READ (*,*) PF,PR,PM,SFCF,SFCR,SFCM
    FCF=2.0*PF*SFCF*TF
    FCR=2.0*PR*SFCR*TR
    FCM=2.0*PM*SFCM*TMH*2.0
    GOTO 636
635 WRITE (*,*) ' '
    WRITE (*,*) ' INPUT POWER OF DIESELS AND GAS TURBINES AT FULL'
    WRITE (*,*) ' SPEED, REDUCED SPEED AND MANOEUVRING (kW).'
    READ (*,*) PSD,PSGT,PRD,PRGT,PMD,PMGT
    WRITE (*,*) ' '
    WRITE (*,*) ' INPUT SPECIFIC FUEL CONSUMPTION OF DIESELS'
    WRITE (*,*) ' AND GAS TURBINES AT FULL SPEED, REDUCED SPEED'
    WRITE (*,*) ' AND MANOEUVRING (g/kWh).'
    READ (*,*) SFCD,SFCGT,SFCRD,SFCRGT,SFCMD,SFCMGT
    FCF=2.0*((PSD*SFCD)+(PSGT*SFCGT))*TF
    FCR=2.0*((PRD*SFCRD)+(PRGT*SFCRGT))*TR
    FCM=2.0*((PMD*SFCMD)+(PMGT*SFCMGT))*TMH*2.0
636 FCRT=(FCF+FCR+FCM)/1000.0
    FCD=FCRT*NRT*1.06
    FCL=FCRT*NRT*0.03
    WRITE (*,*) ' '
    WRITE (*,*) ' INPUT FUEL PRICE ($/t).'
    READ (*,*) FPRICE
    LPRICE=FPRICE*10.0
    FCOSTD=(FCD/1000.0)*FPRICE
    FCOSTL=(FCL/1000.0)*LPRICE
    IF ((ETYPE.EQ.'D').OR.(ETYPE.EQ.'d')) THEN
    MCOSTH=95.0
    ELSE IF ((ETYPE.EQ.'T').OR.(ETYPE.EQ.'t')) THEN
      MCOSTH=65.0
      ELSE
        MCOSTH=65.0+((95.0-65.0)*(PBD/PB))
    ENDIF
    MCOSTD=NRT*TRT*MCOSTH
    PORT=GRT*0.05
    PORTD=PORT*NRT*2.0
    TDOC=FCOSTD+FCOSTL+MCOSTD+PORTD
    TAOC=(TDOC*DAYS)/1000.0
    WCOST=NC*WAGE/1000.0
    BIC=(BINS/100.0)*BC
    TPL=1000.0*NC
    ICOST=(BIC*1000.0)+(TPL/1000.0)
    ACOST=300.0
    CRF=(2.35*ROC)/100.0
```

```
      CCOST=(CRF*BC)*1000.0
      TACOST=TAOC+WCOST+ICOST+ACOST+CCOST
      FCOST=FCOSTD+FCOSTL
      FCOSTY=(FCOST*DAYS)/1000.0
      MCOSTY=(MCOSTD*DAYS)/1000.0
      PORTY=(PORTD*DAYS)/1000.0
      WRITE (*,*) ' '
      WRITE (*,*) ' OPERATING COSTS'
      WRITE (*,*) ' ---------------'
      WRITE (*,*) '                             DAILY (US$)     ANNUAL (K US$)'
      WRITE (*,504) FCOST,FCOSTY
      WRITE (*,505) MCOSTD,MCOSTY
      WRITE (*,506) PORTD,PORTY
      WRITE (*,*) ' '
      WRITE (*,507) TDOC,TAOC
  504 FORMAT ('  FUEL COST                ',F8.0,10X,F8.0)
  505 FORMAT ('  MAINTENANCE COST         ',F8.0,10X,F8.0)
  506 FORMAT ('  PORT CHARGES             ',F8.0,10X,F8.0)
  507 FORMAT ('  TOTAL                    ',F8.0,10X,F8.0)
      WRITE (*,*) ' '
      WRITE (*,*) ' TOTAL RUNNING COSTS (ANNUAL)'
      WRITE (*,*) ' ----------------------------'
      WRITE (*,*) '                              K US$'
      WRITE (*,508) TAOC
      WRITE (*,509) WCOST
      WRITE (*,510) ICOST
      WRITE (*,511) ACOST
      WRITE (*,512) CCOST
      WRITE (*,*) ' '
      WRITE (*,513) TACOST
  508 FORMAT ('  OPERATING COST              ',F8.0)
  509 FORMAT ('  CREW COST                   ',F8.0)
  510 FORMAT ('  INSURANCE COST              ',F8.0)
  511 FORMAT ('  ADMINISTRATION COST         ',F8.0)
  512 FORMAT ('  CAPITAL COST                ',F8.0)
  513 FORMAT ('  TOTAL                       ',F8.0)
  700 WRITE (*,*) ' '
      WRITE (*,*) ' DO YOU WANT TO PERFORM CALCULATIONS FOR'
      WRITE (*,*) ' ANOTHER SCENARIO? (Y/N)'
      READ (*,516) YN
      IF ((YN.EQ.'Y').OR.(YN.EQ.'y')) THEN
      GOTO 701
      ELSE IF ((YN.NE.'N').AND.(YN.NE.'n')) THEN
        WRITE (*,*) ' I SPECIFICALLY ASKED FOR AN "Y" OR AN "N"'
        GOTO 700
      ENDIF
  515 WRITE (*,*) ' '
      WRITE (*,*) ' DO YOU WANT TO PERFORM CALCULATIONS FOR'
      WRITE (*,*) ' ANOTHER VESSEL? (Y/N)'
      READ (*,516) YESNO
      IF ((YESNO.EQ.'Y').OR.(YESNO.EQ.'y')) THEN
      GOTO 514
      ELSE IF ((YESNO.NE.'N').AND.(YESNO.NE.'n')) THEN
        WRITE (*,*) ' I SPECIFICALLY ASKED FOR AN "Y" OR AN "N"'
        GOTO 515
      ENDIF
  516 FORMAT (A)
      STOP
      END
```

APPENDIX G: INDEX TO USED SYSTEMATIC DATA

This appendix describes, for reference, the sources of systematic data used within the technical design framework. These include resistance and propulsion (powering) as well as seakeeping data developed at the University of Southampton and elsewhere.

A comprehensive set of round-bilge semi-displacement hull form resistance data has been assembled. This includes the systematic data of the NPL series [100] and Series 64 [101] for monohulls. The major parameters in both cases are $L/\nabla^{1/3}$ and B/T. In the NPL series the length-displacement ratio varies between 4.47 and 8.3 and the beam-draught ratio varies between 2.19 and 5.49, with the exact range depending on the $L/\nabla^{1/3}$ value. Block coefficient C_B is kept constant at 0.40. Series 64 offers a range of higher $L/\nabla^{1/3}$ values, from 9.3 to 12.4. The B/T ratio varies between 2.0 and 4.0 independent of the length-displacement ratio. Finally C_B is also treated as a parameter in Series 64, ranging from 0.35 to 0.55.

Further systematic data have been generated at the University of Southampton [87], [89]. These are based on an NPL-type hull form but with higher $L/\nabla^{1/3}$ values, thus offering an overlap between the two standard series (NPL and 64). In the Southampton series the ranges of the main parameters are: $L/\nabla^{1/3}$ between 7.5 and 9.5 and B/T between 1.5 and 2.5. C_B is kept constant at 0.40 as in the NPL series.

The speeds covered by the data in the Southampton series reach up to a Froude number of 1.0. Some of the smaller fast ferries operate in slightly higher Froude number and for this reason C_R values have been extrapolated for speeds up to $F_n = 1.1$. This is justifiable on account of the fair and relatively flat C_R curves in higher speeds which makes such extrapolations reasonably safe. Similarly, for Series 64 where the speed variable is volumetric Froude number F_∇, C_R values have been extrapolated for speeds up to $F_\nabla = 5.0$. The new data have been included in the relevant data files, enhancing the scope of the relevant database. The NPL series covers speeds up to $F_n = 1.2$.

These three sets of systematic data collectively offer a comprehensive coverage of parameter values for monohulls. For catamarans however there were no such data that could be used for such investigations. The Southampton series has been generated with the focus on catamarans and offers significant coverage of parameter values. The value ranges for the above-mentioned main parameters are the same as for monohulls and in addition the S/L ratio is varied between 0.20 and 0.50. These systematic data are used for catamaran powering calculations, coded in the relevant computer programs, see Appendix F.

Some of the high-speed catamarans are more slender than those covered by this range of values. For this reason it would be desirable to extend the Series 64 data in order to include catamarans, as this series offers length-displacement ratios up to 12.4. This extension has been attempted by applying catamaran/monohull C_R ratios taken from the Southampton series, with partial success; some extrapolation problems have been encountered. The use of Series 64 for catamarans is therefore not fully possible yet and the completion of this extension is currently undertaken at the University of Southampton [109].

Propulsion calculations are performed using the available systematic data for the Wageningen-B [112] and the Gawn-Burrill propeller series. These are used to perform a standard η_0 optimisation which is included in the relevant computer programs, see Appendix F.

Moving on to seakeeping calculations, the only published systematic experimental data are those which have been generated at the University of Southampton [89]. These cover the range of parameter values of the Southampton series for monohulls and catamarans. A computer program includes these data allowing various calculations to be performed, including motions, accelerations and probabilities of exceeding prescribed response limits.

The seakeeping database currently includes data on regular head seas only. Ongoing research at the University of Southampton is focusing on the extension of the database with data on oblique and beam as well as irregular seas, both for the Southampton and 64 series [145-146]. This includes the generation of systematic data by tests in towing tank, manoeuvring tank and in the open sea. The generation of such data will significantly enhance the scope of the seakeeping module.

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