A Computer-Aided Conceptual Ship Design System Incorporating Expert Knowledge.

by

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SUMMARY

In today's highly competitive shipbuilding market the emphasis is on the production of acceptable design proposals within a very short timescale. A computer-aided conceptual ship design system, which utilises the latest developments in workstation technology, has been developed. It is intended to help reduce the technical and commercial risks associated with the process of tendering for newbuilding contracts. The system as a whole, uses fundamental modelling techniques to enable areas such as dimensions generation, hullform development, layout design, powering estimation, mass estimation, motions prediction, work content estimation and cost estimation to be considered at a much greater level of detail at the concept design stage than was previously possible.

This thesis describes the specification and development of those parts of the overall design system concerned with the generation of vessel dimensions and hullform and layout design. In order to improve the flexibility of the system, a so-called expert system approach has been adopted to provide the mechanism for the control of the design methodology. For this purpose, a unique expert system shell named INCODES (INtelligent COncept DEsign System) was specified and developed. The development of this shell is described in some detail. The application of the INCODES shell to the control of the logic involved in the development of design proposals for containerships is discussed, and the knowledge base developed for the generation of these design proposals is described. The knowledge base is shown to incorporate fundamental procedures for the generation of vessel dimensions and for hullform and layout design, as well as a comprehensive suite of analysis routines to assist in the verification of the design proposals. The knowledge base is also considered to be unique in its treatment of the investigation of the loading arrangements of containership design proposals. The flexibility of the procedures developed is demonstrated by their application to the generation and examination of containership design proposals which possess a range of physical and operational characteristics.

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Martin Welsh.
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CONTENTS.

GLOSSARY OF ARTIFICIAL INTELLIGENCE TERMS.

Alpha-beta algorithm - A game-playing strategy that attempts to reduce a search by cutting off branches in the search space that are not to be evaluated.

Artificial intelligence (AI) - A subfield of computer science concerned with the concepts and methods of knowledge representation and problem solving.

Attribute - A property of an object.

Backtracking - The process of moving backward through a series of inferences to discover or trace a reasoning pattern or to explore an alternative path.

Backward chaining - An inference engine control strategy in which inferences are made by starting with a conclusion and working backward in an attempt to find the facts to support the conclusion.

Boolean operators - The operators used in propositional calculus, which include AND, OR, and NOT.

Breadth-first search - A search strategy in which all nodes at one level are pursued before moving to the next level of detail.

Cognitive modelling - The development of theories, concepts and models of the human mind and how it functions.

Conflict resolution - In a production system, the process of determing which rule to fire when two or more rules match the specified facts in the working memory.

Control component - The part of the inference engine or rule interpreter which determines the sequence of use of rules.

Database - In a knowledge system, this generally refers to the working memory.

Depth-first search - A search strategy in which details are pursued as far as possible until

a conclusion is unable to be proved true.

Domain - A definable extent of knowledge about a subject.

Expertise - Heuristics and knowledge possessed by some humans in a particular domain. Expertise is gained by amassing large amounts of knowledge in a domain and organising it into appropriate hierarchical segments so that it can be applied to the solution of problems in the domain.

Fact - A statement of premise that is true. A fact can consist of an attribute and an associated value.

Firing - The action in a production system inference cycle in which a conclusion is added to the working memory or a specific output action is initiated.

First-order logic - An extension of propositional calculus with quantified variables.

Forward-chaining - An inference engine control strategy in which inferences are made by applying facts to rules, resulting in conclusions that are supported by the facts.

Frame representation - A type of knowledge representation in which objects are stored with one or more attributes. The value for each attribute is stored in a slot. A frame is a set of slots related to a specific object.

Heuristic - Informal knowledge used to improve the efficiency of search in a given problem space.

Hierarchy - A relationship of concepts or objects in which some are subordinate to others.

Inference - A reasoning process in which new facts are derived from known facts.

Inference engine - That part of a production system that derives new facst from known facts in the knowledge base.

Inheritance - A process in which attribute values of one object are derived from an object class in a hierarchy.

Knowledge - A collection of facts, relationships, and heuristics which can be used to solve

problems.

Knowledge base - That portion of a knowledge system that consists of facts and rules. In a production system it consists of the rulebase and working memory.

Knowledge engineer - An individual skilled in assessing problems and building knowledge systems. The term implies training in cognitive science, computer science, knowledge systems, and other aspects of artificial intelligence.

Knowledge representation - The method that is used to encode facts and relationships in a knowledge base.

Knowledge systems - A class of computer programs that use knowledge and inference procedures to solve problems.

Object - An entity in a knowledge system that can have one or more attributes.

Parsing - The act of decomposing a statement into its component symbols and determining its syntax.

Predicate - A function with a value of TRUE or FALSE.

Predicate calculus - An extension of propositional logic that permits the use of quantified variables. Propositions can have the value TRUE or FALSE. The language provides a means of expressing symbolic relationships.

Problem reduction - A control heuristic in which goals are defined in terms of sub-goals in a hierarchical goal structure.

Problem solving - The process of achieving a desired goal starting from an initial state. The solution involves moving through a problem space in a sequence of operations.

Problem space - A representation of all the possible states in the solution of a problem and the relationships between the states.

Production - An IF...THEN rule that consists of a premise or antecedent and conclusion or consequence.

Production system - A type of knowledge system in which the knowledge is stored as

productions or a collection of IF...THEN rules. A production system consists of a knowledge base, an inference engine, and working memory.

Propositional logic - A formal logic language in which variables can only have the value of TRUE or FALSE and boolean operations can be performed between the variables.

Semantics - The meaning of an expression or statement.

Semantic network - A type of knowledge representation in which the objects and values are reprsented as nodes with links indicating relationships between the nodes.

Shell - A tool that can be used to develop a complete knowledge system consisting of the inference engine, a working meomry, and optional auxiliary components such as a knowledge acquisition subsystem or explanatory interface.

Symbol - Any component of a knowledge structure.

Triggering - A process in the inference cycle of a production system in which a rule is selected for firing.

Working memory - The storage used for the facts in a production type of knowledge system that have been ascertained as true or not true during a particular consultation. Also called a database.

CHAPTER 1

The Conceptual Design of Ships.

SUMMARY.

This Chapter describes the background to the decision to develop a computer aided design system for use at the concept stage of the ship design process. The various elements of the complete design system are discussed, and the modular nature of the system is described. The proposed system will be shown to cover areas of the ship design process which would have not previously been considered as concept design activities.

The general outline specification of the system is discussed in terms of hardware and software configurations. The part of the overall system of which this thesis is the subject is discussed, and the extent of the work covered by this particular aspect of the complete research project is outlined.

1. Introduction.

The design spiral [1.1] is often used to illustrate the iterative nature of the ship design process. The earliest stage of the design process, the concept or pre-contract stage, is perhaps the most important, as any decisions made at this stage have a far-reaching effect on the overall quality of the final design proposal. The ability of a final detailed design to achieve required standards in terms of functionality and producibility will often depend upon decisions made at the concept stage. The importance of this first cycle in the design process has long been recognised by those involved in the specification and development of ship design proposals, but up until quite recently has been an area largely ignored by the developers of ship design software. In todays competitive shipbuilding market, the emphasis is on the rapid response to the enquiries of prospective owners whilst minimising the risks associated with the tendering process,

requiring that there is a high degree of confidence in the technical specification and price associated with a particular tender. The fact that many newbuilding contracts are for sophisticated one-off vessels, of a type which a particular shipyard may not have had any previous experience, can exacerbate the potential technical and commercial risk involved in the tendering process.

Developing a ship design proposal will usually involve attempting to satisfy a set of often conflicting requirements. As a result of this, most design proposals will be a compromise to some extent. In many cases the best compromise can only be achieved by undertaking some kind of multi-objective optimisation study or by carrying out a series of parametric-variation type investigations. Without the availability of suitable computer software, investigations of this nature would not be feasible in the short time scale associated with the preparation of design tenders, and, as previously mentioned, the amount of suitable software for use at this stage in the design process is very small indeed.

2. Computers in concept ship design.

Applications of computer technology can be found in one form or another in practically every aspect of the ship design and production process [1.2] from the analysis of ship structures, to the numerical control of material burning and forming equipment. The technical activities of the ship design and production process in particular have received considerable attention with large-scale investment in computerised systems in ship design and other technical areas. Computer aided draughting is an area which has enjoyed particular success in the shipbuilding industry with the utilisation of systems such as CADAM [1.3], which emulate the manual preparation of drawing-based production information. In addition, many of the other computer applications to be found in ship design departments are tools for the analysis of various aspects of design proposals, such as geometric hullform properties and powering characteristics, and do not offer assistance in the generation of the required models (mathematical, drawing-based, or geometric) of the physical entity being considered. In fact, few of the computer aided ship design systems available could be considered as real design aids.

The concept stage of the ship design process is an area where there are very few useful software tools of any nature, be they design or analysis. The shortage of suitably

trained and qualified technical personnel [1.4] can often exaggerate the effect of insufficient software packages for use in the early design stages. Most of the software tools available are intended for use at the later stages of design development where the various data concerning the proposal are of a fairly high standard and are relatively complete in their description of the proposal. The quantity and quality of data demanded by these systems makes them largely unsuitable for use at the stage in the development of a design when the information available may be incomplete and of a relatively poor standard.

Some software solutions have recently been developed which attempt to bridge this significant gap in the range of computer based tools available to the designer. Notable attempts include the CODES system [1.5], the HOSDES system [1.6] and the RAPID system [1.7].

3. The British Shipbuilders/Newcastle University concept design system.

Despite these recent attempts to provide viable concept ship design software tools, a considerable need for an integrated concept design system was perceived in early 1985 by a working group formed by British Shipbuilders Limited and the Department of Naval Architecture at the University of Newcastle upon Tyne [1.8]. This group developed the initial proposal for a concept design tool which would encompass the full range of activities associated with the early design stages, such as the generation of ship dimensions, hullform design, layout arrangement, naval architecture calculations, mass estimation, resistance and propulsion, motions assessment and also work content and cost estimation. Work on this ambitious project began in late 1985 with the development of modules covering hullform design, layout arrangement and naval architectural calculations, and, as a separate research project, structural arrangement and steelmass estimation. Since then other modules have been, or are being developed for inclusion in the system, as shown in Figure 1.1.

The primary aim in the specification and development of the joint British Shipbuilders/Newcastle University conceptual ship design system was to provide a set of integrated computer based design tools which would allow the designer to design and analyse a wide range of ship design proposals with a degree of accuracy commensurate with the particular level of design activity. Advances in computing technology, both in terms of hardware and software design, made such a system feasible. Whilst the main aim

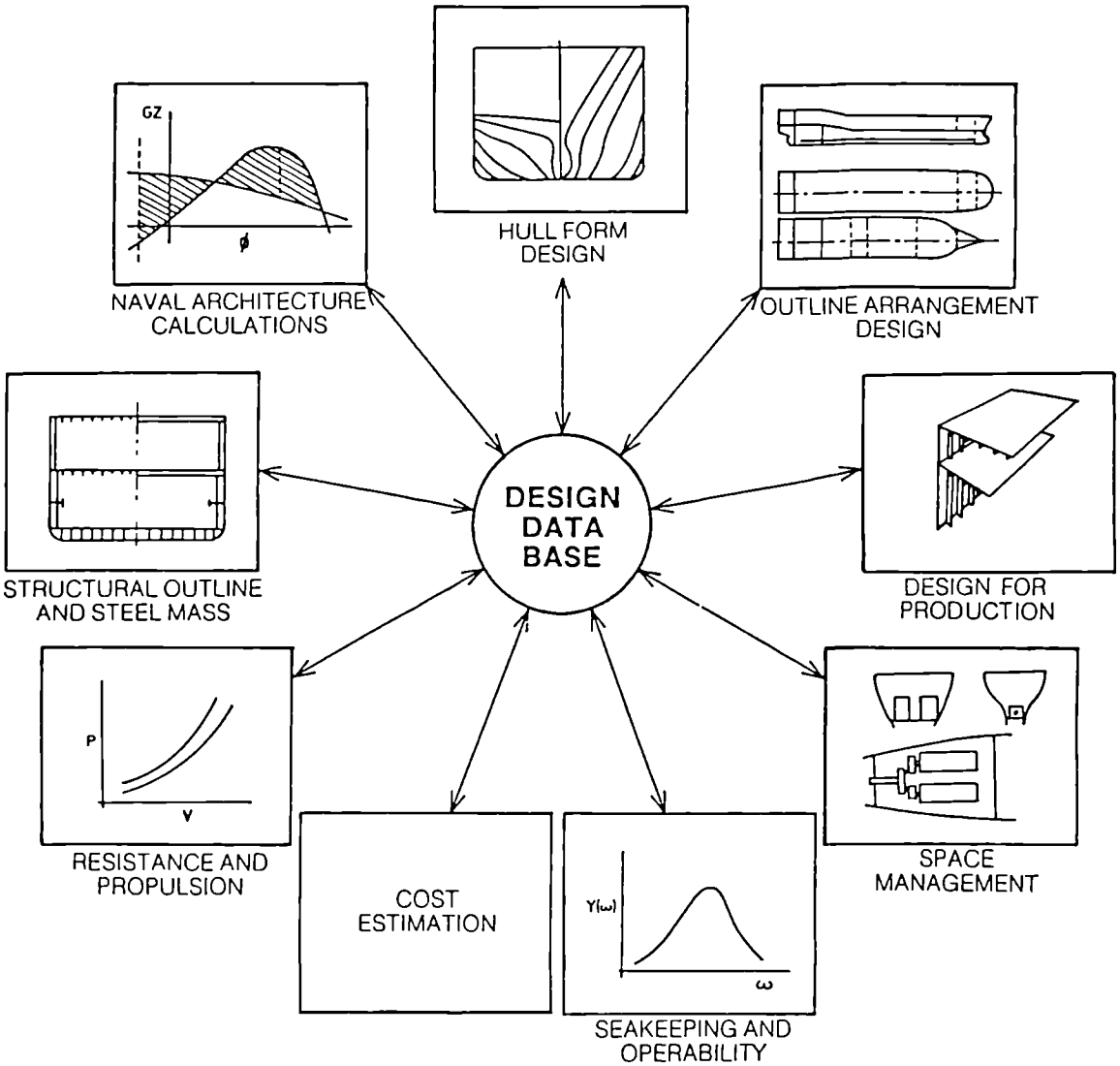

Figure 1.1 The main modules of the concept ship design system.

of the research project was to develop an integrated concept design environment which would provide the user with absolute control over every aspect of the development of design proposals from the generation of preliminary dimensions to the definition of build strategies, it was envisaged that the modular nature of the system would also allow the various components to be used as stand-alone units. This modularisation of the system also permitted rapid development and prototyping of the individual system components.

The main requirements for the system were concerned with ensuring its suitability for use at the concept design stage. It was envisaged that the system would often have to operate with the bare minimum of information of varying quality and as such a certain level of expertise would have to be exhibited by the system to allow it to adjust its level of complexity of operation to suit. This would require, for example, the incorporation of default values for design parameters and operational characteristics.

The system was also to have a high reliance on interactive computer graphics for both data input and data modification, therefore greatly speeding up the initial definition of design proposals. Graphical representation would also be extensively used for the verification of design data so that errors and ommissions could be quickly realised and corrected; a feature required by many of the current quality standards.

Whilst the system was intended for use primarily in situations where the amount and quality of the available data would be quite variable, the structure and methodology of the system would be such that increased accuracy could be obtained from the various procedures used as the standard of data improved. As such, the use of approximate calculation methods would be avoided in favour of full procedures wherever possible, thus allowing the system to be used at later stages of the design process with a high degree of user confidence.

One of the main features of the system was to be its accessibility, that is there would be no reliance on the use of high cost mainframe or mini-computers. It would be developed for use on low cost engineering workstations, a move which would immediately increase the potential user-base for the system.

3.1 System hardware and software.

The decision to develop and implement the concept ship design system on a low-cost

hardware configuration, considerably limited the choice of available computer systems which could effectively support a design system of the size and type being considered. At the time of the conception of the project in 1985, the choice of hardware was basically between the products of manufacturers such as IBM, Hewlett Packard and Compaq. In view of the existing commitment of British Shipbuilders Ltd. to the products of IBM, a decision was made to utilise an IBM PC-AT machine as the basic central processing unit for the system. Other equipment, such as the graphics screen, digitiser, printer and plotter were obtained from various manufacturers such as Cambridge Graphics, Calcomp, Graphtec and Epson. The complete workstation hardware is shown graphically in Figure 1.2. In addition to the requirement for hardware, there was also a need for software which would be used in the development of the system. For example, as the system was to incorporate a large number of graphical elements, there was a need for a graphics primitives library which could be used in the graphics procedures. The GINO-F graphics library [1.9] was chosen to meet this requirement the most established of the available graphics packages for the IBM/Cambridge hardware configuration. In addition to the graphics library, there was also a need for a source code compiler, and as FORTRAN 77 had been selected as the development language, the Microsoft Ltd. FORTRAN 77 [1.10] compiler was chosen as this provided immediate compatibility with the GINO-F graphics library.

As development of the system began, a decision was made to change the target machine from the IBM PC-AT to a UNIX [1.11] based engineering workstation from SUN Microsystems. The new choice of hardware not only provided a much improved user interface for application development, but also had a much higher processor speed which would greatly reduce the time taken for program execution. The windowing environment of the SUN workstation also permitted a better interface to be developed for the end user of the design system with graphical and textural information being displayed on a single display device but within different windows. The ability of the windowing environment to run multiple applications, by time-sharing the central processor, also presented significant improvements over the IBM workstation. This feature provided the ability to run several applications simultaneously, therefore considerably reducing the time taken to carry out detailed analysis, etc. of design proposals. The SUN Microsystems operating environment also provided the necessary software tools for the development of the design system, including an ANSI FORTRAN 77 compiler [1.12] (complete with an interactive debugging tool) and a graphics primitives library [1.13],[1.14]).

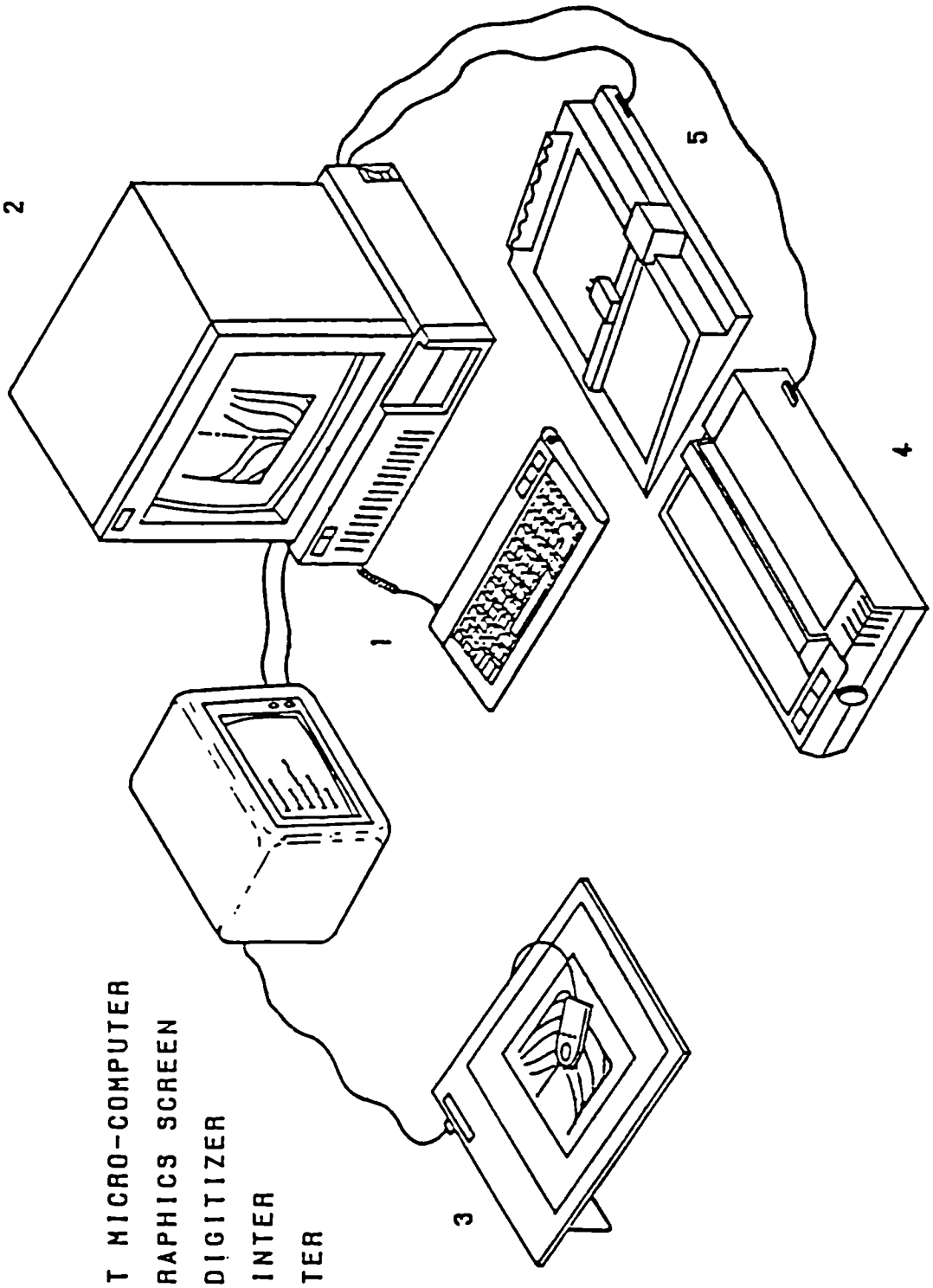

Figure 1.2 Micro-based workstation hardware configuration.

In retrospect, the decision to revise the choice of hardware for the development and implementation of the ship design system was quite correct as this resulted in the production of a much more reliable and robust product with a vastly improved user interface and considerably improved overall performance.

3.2 Scope of the project.

As discussed previously, the overall aim of the research project was to produce a fully integrated conceptual ship design system covering all of the accepted areas of the conceptual ship design process together with some additional areas which had not previously been considered as conceptual design activities. It has also been mentioned that work was initially commenced on two particular aspects of the project, one of which was the dimensions estimation, hullform design, layout design, and naval architectural calculation module. It is this particular module of the system of which this thesis is the subject.

3.2.1 General description of the module.

This module is perhaps the most important in the overall design system as much of the data required by the other system elements are initially determined by the various components of the module. For example, the main dimensions as generated by the module are required by all of the other modules, as are the hullform description and layout particulars. Without this information the system as a whole could simply not function.

It is quite obvious that the module of the design system being described here consists of elements which are of a fairly general nature and can therefore theoretically be applicable to the design of a wide range of vessel types, such as general cargo, roll on - roll off, containerships, passenger vessels, bulk carriers, and so on. These general procedures include the basic analysis routines such as the hydrostatic particulars procedure, intact stability, longitudinal strength and powering estimation routines. In addition to the analysis components of the module, the hullform development element and parts of the layout design procedure could also be expected to be fairly general in their range of application. The only component of the module which could be considered as being completely ship-type specific is the dimensions estimation procedure, as the methods available for the estimation of main dimensions vary according to whether the vessel is capacity or deadweight limited, as defined by Watson [1.15],

and even within these broad categories there are different approaches available depending on the specific type of vessel being considered.

In the context of the design system being described here, it was considered essential to limit the ship-type dependent components of the system to a single class of vessel. This not only promised to make best use of the resources available for the development of the system, but also allowed the suitability and effectiveness of the proposed methodology to be fully assessed.

With this consideration in mind, subsidiaries of British Shipbuilders were approached with the aim of identifying the type of vessel in which there was some degree of interest at that time. This exercise revealed the containership as being the vessel type in which it was considered that interest would be maintained for the foreseeable future. It was therefore decided to concentrate upon the containership when considering the type-dependent aspects of this module of the conceptual design system.

The estimation of the main design characteristics of a design proposal, such as the principal dimensions and the initial general arrangement, is an activity which has considerable reliance on the expertise and knowledge of the individual designer. Many computer-based procedures have been proposed for the determination of the main particulars of container vessels, but none actually incorporate facilities which will reflect minor as well as major modifications to the specification of the design proposal. In order to overcome this shortcoming of previous procedures and develop a true design assistant, it was considered necessary to build into the system the knowledge and expertise of practising designers as well as the requirements of regulatory bodies, shipyard standards and accepted good practice. It was envisaged that such a system would be able to exhibit a form of intelligence in that it could use its in-built expertise and knowledge to generate and analyse design proposals against a set of specified requirements, and to implement changes should the analysis show the proposal to be deficient in any respect. It could also use its knowledge of design parameter relationships to assess the effects of design modifications and ensure that all information relating to the proposal was constantly updated.

Normal computer systems do not facilitate the incorporation of the type of knowledge described above, but recent developments in the field of computer science coupled with the previously described advances in workstation technology, do provide the means

of producing such an intelligent computer system. To assess the feasibility of an intelligent concept design system it was necessary to look to the branch of computer science known as artificial intelligence, and in particular at the area concerned with so-called expert or knowledge based systems.

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CHAPTER 2

Artificial Intelligence and Knowledge Based Systems.

SUMMARY.

This Chapter describes the area of computer science known as artificial intelligence, and in particular that aspect of it concerned with expert or knowledge based systems. The various aspects of these so-called expert systems are described together with the criteria used to assess the suitability of potential applications. The benefits to be gained from the adoption of an expert system based approach are discussed, as are the associated disadvantages, so that a judgement can be made as to whether this approach would appear to be suitable for the conceptual ship design system being considered.

Examples of existing expert system applications are given in both engineering and non-engineering areas. A summary of the various expert system development techniques is given, together with an indication of the advantages and disadvantages associated with each one.

1. Introduction.

Knowledge based systems, or expert systems as they are more often called, are a component of the branch of computer science known as artificial intelligence. In general terms, artificial intelligence could be described as that property exhibited by a machine when carrying out a process or operation which, if performed by a human being, would be said to require some degree of intelligence. From this definition it can be appreciated that the field of artificial intelligence (A.I.), is very broad and encompasses a wide range of interests and areas of research. The origin of modern interest in artificial intelligence can be traced back to 1956, the year in which the first true knowledge based system was introduced at Dartmouth College in the United States. Nowadays, the term artificial intelligence is applied to a wide range of interests such as knowl-

edge representation, expert systems, problem solving, natural language interfacing, learning, cognitive modelling, strategy games, vision and robotics. The connections between these areas is shown in Figure 2.1.

Although each of the separate components of the field of artificial intelligence receive much attention as individual areas of interest, many of the techniques developed in these separate areas are applicable over the full range of artificial intelligence related subjects. Knowledge based systems are an example of an area of artificial intelligence which relies to a large extent on the application of techniques developed primarily for use in other areas. For example, knowledge based systems draw heavily upon the work done in the areas of knowledge representation, problem solving, and natural language interfacing.

2. Overview of the main components of artificial intelligence.

As previously mentioned, some aspects of the artificial intelligence field are of direct relevance to the development of knowledge based systems. A brief description of each of these areas is given below, while a more detailed explanation of the available techniques and methods will be given in the Section 3 which is concerned with knowledge based systems.

2.1 Knowledge representation.

Knowledge representation is without doubt the most important aspect of artificial intelligence as it provides the basis for nearly all of the other related areas. Any application of artificial intelligence technology, be it a robotics application or a simple strategy game system, relies on the incorporation of knowledge of some description. Knowledge, in any form, is concerned with the realisation of the objects, relationships and procedures associated with a particular domain or area of interest. Many tools and techniques exist for the representaion of the various forms of knowledge, but each is different due to having been developed to satisfy a certain need. Rarely is any knowledge representation method or technique applicable over a range of domains. It is therefore universally agreed that the long-term goal of knowledge representation research must be the determination of a general model which would allow the representation of the knowledge associated with any area of interest.

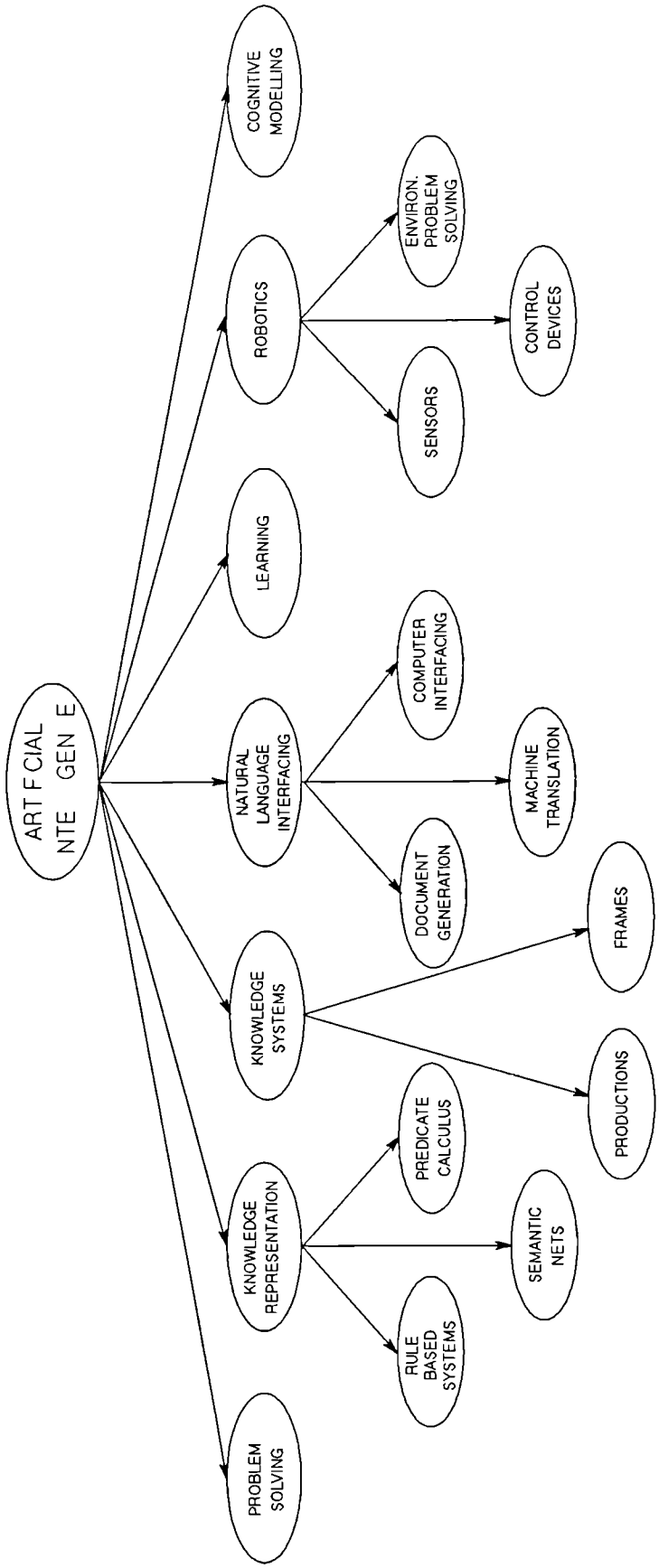

Figure 2.1 The components of artificial intelligence.

2.2 Problem solving.

Problem solving can be defined as the process of finding a way of progressing from some initial situation to a final desired goal. When considering the techniques used to solve problems, a comparison can be made between the human brain and the computer. The brain, for example, can solve problems very effectively by the use of deductive reasoning, procedural analysis, analogy and induction, together with the compounding effect of the learning process. Computers, on the other hand, can only usually be applied to solving problems using deductive reasoning and procedural analysis, without the benefit of learning from experience. Problems usually fall into one of three main groups :

- those which are solved using procedural analysis,
- those which require analogy and intuition,
- those which are solved using deductive reasoning.

The first class of problem is best solved by the computer as the problem is defined in terms of a series of predefined steps which are easily followed to arrive at a solution. Those problems which involve analogy and intuition are best solved by the human brain without the use of a computer. The third class of problem, those involving deductive reasoning, can be easily solved by the human brain, and can also be tackled by the computer by using knowledge based or expert systems.

2.3 Natural language interfacing.

This area of interest concerns the development of effective and efficient means of communication between the computer and the human user. The problem exists as a result of the way in which knowledge is stored and processed by the computer in comparison to the methods used by the human brain. Language, the means of communication, can be considered as comprising the symbols used to represent knowledge together with the rules which govern their use, the syntax. Natural language interfacing is the means by which the language used by the human user, with its associated symbols and rules, can be understood by the computer and translated into the language it uses for knowledge storage and manipulation. The reverse is also true in that the language use by the machine must also be translated into a form which can communicate information to the human user. Requiring the computer to understand the natural

language of the user rather than the user having to communicate using specially developed languages and syntaxes, either high or low level, will have obvious and far reaching effects on the way in which computer systems are both developed and used in the future. For example, there is currently considerable interest in the development of natural language interfaces to make applications such as databases and spreadsheets much more user-friendly and accessible and so hopefully more attractive to the potential customer.

3. Knowledge based systems.

An expert or knowledge based system can be defined as an intelligent computer program that utilises knowledge and inference procedures to solve problems that are considered to be difficult enough to normally require human expertise for their solution. In a typical expert system, as illustrated in Figure 2.2, the knowledge about the particular domain under consideration is held in what is known as a knowledge base. This knowledge base is interrogated and interpreted by a mechanism known as the inference engine. This inference engine can be considered to represent the reasoning process in in that its function is to match facts to the condition part of knowledge base rules in order to arrive at conclusions and hence generate more facts. The way in which the inference engine determines the sequence of invoking the rules is governed by the control strategy on which it is based. The available control strategies and other features of the inference engine will be discussed in more detail in Section 3.5.5.
The main features of an expert system which distinguish it from normal computer-based systems can be summarised as follows :

- The area of application of the system is usually limited to a single domain.

- The knowledge base and inference engine are separate entities. The inference engine can be attached to knowledge bases which relate to completely different domains to create new expert systems.

- It is best suited to the solution of problems which involve deductive reasoning, i.e. where the rules or heuristics are expressed in terms of IF .... THEN antecedents and conclusions.

- Conclusions are explained to the user and the reasoning behind the

achievements of goals can be demonstrated.

- The output is qualitative rather than quantitative.

- The system is designed on a modular basis and can grow incrementally with the knowledge base.

3.1 Applications of knowledge based systems.

Knowledge based systems can be found in some form in a wide range of disciplines ranging from medical diagnosis to plant monitoring and control.

Some of the better known and more successful expert system applications have been in the field of medicine, the most frequently quoted examples being MYCIN [2.1], PUFF [2.2], and INTERNIST [2.3]. Other, non-medical systems, which are often cited as being representative of practical expert system applications, are DENDRAL [2.4], and PROSPECTOR [2.5].

DENDRAL, one of the first expert systems which could be considered as utilising specific domain dependent expertise for problem solving, is concerned with proposing and explaining chemical structures from analyses data. PROSPECTOR was developed to analyse data concerning geological structures. Using the programmed knowledge of nine experts, PROSPECTOR has been successful in identifying the location of ore deposits worth millions of dollars, which all nine experts failed locate.

All of the above systems illustrate the expansion of the computers problem solving ability to include those areas which are based on deductive reasoning.

In the context of engineering design in general, and marine design in particular, the potential benefits to be gained from the application of expert system technology are enormous. Design is a discipline combining theoretical understanding with considerable expertise and judgement. At present the accepted role for computer systems in engineering design is as fast calculators concerned with the solution of problems which are specified in procedural terms. A move toward knowledge based systems enables the expertise of experienced designers to be used to produce a system which can use its knowledge of the design process to suggest solutions, propose methods, and offer guidance. Such a system would be a design assistant and would take on an active rather than a passive role in the design process. One of the main advantages of an

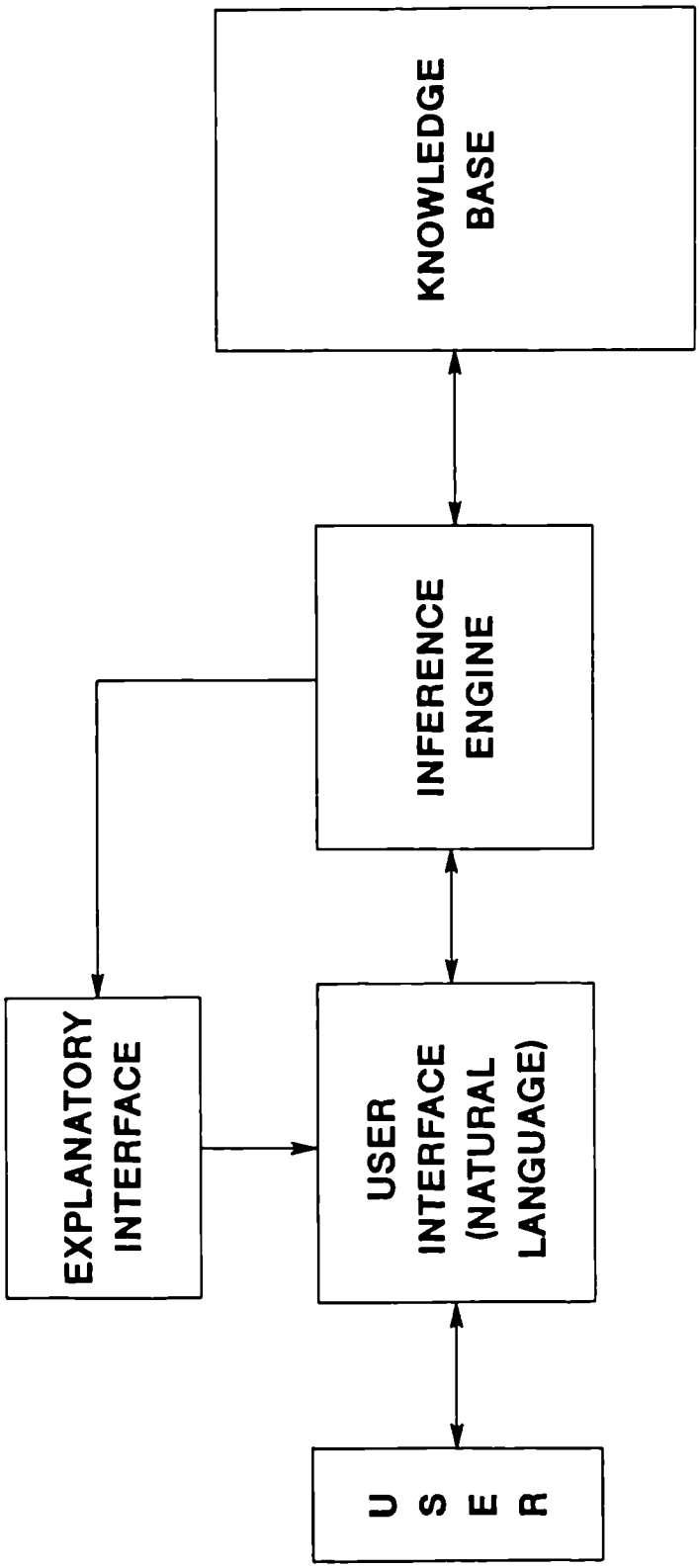

Figure 2.2 The components of a typical expert system.

expert design assistant would be its ability to draw upon knowledge covering a much broader area of expertise than a single designer. In the marine context, such a system could incorporate expert knowledge covering a wide range of activities such as hull-form design, machinery selection and economic analysis.

Considerable advances have been made recently in the development of expert system based design aids in a wide range of engineering disciplines. Typical non-marine applications include those by British Petroleum, whose GASOIL expert system [2.6] is used to design oil and gas separators, and the McDonnell Douglas Aircraft Corporation in the United States which has developed an Icad based system which attempts to provide an intelligent aid to the design and manufacture of aircraft components [2.7]. Both of these projects are typical of those undertaken by large engineering concerns and the scale of the committment to the development of such systems (400 personnel in the case of McDonnell Douglas) is indicative of the high degree of return which is anticipated from the implementation of these applications. In the marine field, the number and range of applications of knowledge systems continues to increase. These developments cover a wide range of activities within the marine industry and vary considerably in their level of complexity both in terms of the problems to which they are applied and the techniques which form the basis of the systems. Examples of these marine related knowledge systems include the DESIGNER system [2.8], the LIFT system [2.9], SEAMAID [2.9], the GEODES system [2.10] and the Ship Evaluation and Design System [2.11].

The DESIGNER system is intended to be a knowledgeable colleague for the modelling and exploration of numerical relationships in engineering design. It is envisaged that the DESIGNER system could form the basis of any engineering design model where it was required to explore the nature of relationships between various design parameters.

LIFT is an expert system based planning aid for North Sea oil platform operations which attempts tackle the considerable problems associated with transportation and installation of offshore structures. The system consists of various knowledge modules which act in both predetermined and non-predetermined ways, and applies heuristics in order to make successive moves towards a solution. The knowledge bases cover areas of offshore operation including mobilisation, manouevring, positioning, pile-handling, lifting and ballasting. The LIFT system is a good example of a comprehen-

sive practical application of knowledge based system techniques to the solution of a complex engineering problem.

SEAMAID is a knowledge based system for the semi-automatic generation of prototype designs of a particular type of offshore loading system. It relies on the definition of design constraints by the user (hence the semi-automatic nature of the prototype generation) and the rules taken from a knowledge base to enable the production of design proposals for offshore terminal structures. At the present time, SEAMAID is still undergoing considerable development, and as such, the design proposals which it produces tend to be of a rather impractical nature. The impracticality of the proposals illustrates the danger of relying too heavily on heuristics, as this type of knowledge is notorious for the inclusion of contradictions. Despite the problems associated with it, the SEAMAID system shows considerable promise, and should, upon completion, provide a useful conceptual design aid for use in the offshore industry.

The Ship Evaluation and Design System being developed at the University of Ulster, attempts to tackle the area of conceptual, mission-orientated ship design. The system adopts a fairly simple rule-based approach to develop design proposals with the emphasis being on the functionality of the vessel under consideration. It is also anticipated that the system will be of particular benefit to ship owners, operators and charterers, who are faced with the problem of having to choose between alternative design proposals and between vessels available for sale or charter. Once again this system is yet to be completed, but is an example of how knowledge based systems can be applied to the solution of marine related problems.

The above examples are only a selection of the many marine related knowledge based systems in use or under development. The scale of interest in the application of knowledge based systems within the marine field, is a measure of the potential which the discipline can see in this particular branch of computer science.

3.2 Assessing the suitability of a proposed application.

As with any application of information technology techniques, some problems are more suited to solution by knowledge based systems than others. In general, the suitability of a proposed application can be assessed by comparison with the following criteria :

- Knowledge based systems should be used primarily in situations where

the knowledge and data are largely invariant with time.

- The solution space should be relatively small.

- The problem should be based on deductive reasoning as this is the type of problem solution to which knowledge based systems are best applied.

- The problem must be easily specifiable. Unless the guesswork, intuition and feel used by human experts can be turned into firm rules, an expert system cannot be developed.

- The domain must be well bounded. The tasks carried out by human experts tend to overlap with one another. That part of the task which is to be automated must be clearly defined.

- The expert or experts must be willing and available. Some experts may feel threatened by the introduction of the new technology and so be reluctant to communicate their knowledge.

- Consideration must be given to the proposed end-user of the system. The system and associated documentation must be suitable for use by those for whom it was intended.

- Management support must be forthcoming. Those who commission the expert system must be aware of the time and effort involved in development of applications, and they must appreciate that the system may never be fully implemented in the form which was intended.

- The project must be cost effective. If the combined cost of system development, hardware and training, is greater than the anticipated benefits, then the system is hardly worth developing. Obviously, the organisation is benefitting from gaining experience in an area of advanced technology, but this cannot easily be expressed in financial terms.

3.3 The limitations of knowledge based systems.

Despite the success of many of the expert system applications which have been developed and implemented, most of the present examples have a considerable number of limitations when compared to the human expert. These limitations can be summarised as follows :

- Many applications are difficult to use by anyone except the person who created the knowledge base.

- The time taken by some systems to process information and interrogate the knowledge base means that they are very slow when compared to the human expert.

- The limited extent of the expertise of a particular application means that the knowledge systems ability tends to end abruptly.

- The task of extracting knowledge from the human expert and putting it into a format which can be understood by an expert system can often present considerable problems.

- The inability of expert systems to exhibit common sense beyond that explicit in the knowledge base limits the effectiveness of present expert system applications.

- The size of the expert system domain must be limited. The application should be restricted to those problems which can be solved in a time span ranging from a few minutes to a few hours.

- Expert systems can only be applied to those areas in which experts exist.

- Expert systems cannot solve problems by analogy or intuition, unlike the human expert who will often make decisions based on feel which are in direct opposition to the conclusions which would be drawn by simply taking the available factual evidence into account.

3.4 Reasons for adopting expert system technology.

According to Lowe [2.12] there are three main reasons for adopting an expert systems approach to problem solving :

- Knowledge preservation.
- Multiplying the effectiveness of staff.
- Low cost knowledge dissemination.

3.4.1 Knowledge preservation.

The preservation of knowledge is obviously very important in the engineering design field where vast amounts of information and data relating to design proposals are generated. In the marine industry especially, there is considerable reliance on the use of historical information. Very few ship design proposals are developed without recourse to previous designs or basis vessels.

Capturing and preserving knowledge ensures that knowledge and expertise does not disappear with the departure of the designers and engineers who have developed it. This is particularly important in industries, such as the marine industry, where periods of intense activity in certain areas are followed by long periods of relative inactivity. The re-generation of interest in a particular area, following a period of inactivity, can often expose weaknesses due to those personnel with relevant experience having left or retired from the company.

3.4.2 Multiplying the effectiveness of staff.

The recording and documentation of design information can often prevent the repetition of work previously done with the associated waste of time and effort. The knowledge possessed by design personnel can often be used to considerable effect by those outside of the design office. For example, the salesman could use a design-oriented expert system to advise potential clients without having to constantly refer to the design office for technical advice and guidance.

3.4.3 Low cost knowledge dissemination.

Once the knowledge base has been set up and the expert system created, the expertise contained in it can very quickly be made available to a large number of personnel

simply by copying the relevant information between the required computer systems. The integrity of the actual structure of the knowledge contained in the expert system can be maintained quite easily by only distributing the run-time image of the knowledge base. This also permits expert systems to be distributed on a commercial basis without the fear of commercial confidentially being compromised.

3.4.4 Additional advantages.

In addition to the three main reasons for adopting expert system technology outlined above, a number of additional benefits could be expected. These can be summarised as follows :

- An expert system is not biased in so far as it takes into account all of the available information and adopts a systematic approach in its search for a solution to the current problem.

- The knowledge base can be very large, and, once established, the knowledge contained in it will never be lost (unlike the human expert who may lose certain knowledge or expertise unless it is constantly accessed and used).

- Expert systems are not affected by outside influences unlike the human expert whose judgement can often be tainted by factors outside of the particular problem domain.

Despite all of the above mentioned advantages, expert systems will never completely replace the human expert, but will be seen to be a valuable assistant enabling him to solve problems much more quickly and effectively than would previously have been possible.

3.5 Components of an expert system.

A normal computer program consists of a series of defined steps stored in memory which are executed to to arrive at a desired solution. In contrast, an expert system has practically no procedural elements and is largely data driven. A typical expert system comprises three main elements as indicated below :

- The knowledge base.
- The working memory.
- The inference engine.

In support of these elements will usually be found a user interface and an explanatory/advisory component.

3.5.1 The knowledge base.

The knowledge base is that part of the expert system which contains the knowledge and expertise associated with a particular domain. This knowledge will usually be of one of two types, factual or rule-based. Factual knowledge is that type of knowledge which can be derived from text books concerned with the problem area, and, in the case of marine design, from the requirements of Classification Societies and other governing bodies. Rule-based knowledge comprises the heuristics, good practice, accepted standards, and judgemental reasoning which the human expert applies to the solution of problems within the particular domain. The choice of technique used to represent the knowledge associated with a subject will largely depend on the nature of the problem under consideration and the format and structure of the available knowledge. Careful consideration must be given to the choice of knowledge representation technique to ensure that it is compatible with the problem under consideration, as the wrong choice will seriously effect the viability of the proposed expert system. The available knowledge representation techniques together with their areas of application are discussed in the following section.

3.5.1.1 Knowledge representation.

3.5.1.1.1 Production rules.

Production rules form the basis of a class of expert system known as a production system. In this type of system the knowledge is represented by means of rules which are normally of an IF...THEN construct, for example :

<u>RULE 1 :</u>
IF ship breadth is less than or equal to 32.2 metres
THEN ship size is panamax

RULE 2 :
IF actual vcg is less than or equal to maximum vcg
THEN intact stability is satisfied

As can be seen from the above examples, a production rule comprises two parts; the antecedent or premise and the consequent or conclusion. The antecedent is a clause or a collection of clauses connected by logical qualifiers and operators such as AND and OR. The conclusion represents the action to be taken upon satisfying the preceeding clauses. The rules represent the relationships between the antecedents and the conclusions.

The parameters contained within the rules, which are the subject of the comparisons and evaluations which enable conclusions to be reached, are known as symbols, and it is the processing and manipulation of such symbols with which production systems are concerned.

In the above examples the symbol relationships are based on classical logic, that is the truth or falsity of the conclusions is absolute and there is no uncertainty involved. Classical logic is only capable of representing two states, true and false, whereas in many real situations there may be some degree of uncertainty in the relationships between the antecedents and the conclusions. This two state logic is commonly refered to as boolean logic. Uncertainty can be incorporated by extending classical logic to allow for relationships which are other than completely true or completely false. A number of techniques exist for the representation of uncertainty, with the more widely used ones being indicated below :

- extended boolean logic
- multi-valued logic
- fuzzy logic .

Although in many cases the incorporation of uncertainty in knowledge representation is a desirable feature, techniques such as those identified above result in production rules being complicated by the addition of a parameter which indicates the level of truth associated with the statement. This can lead to a vast increase in the complexity of the knowledge base which will appear much more cluttered and so be more diffi-

cult to read and understand.

Extended boolean logic.

With this logic representation technique, the two states of classical logic, true and false, are extended to include a third, unknown. Despite the increase in complexity of the knowledge base, the inclusion of this third state has a considerable and beneficial effect on the flexibility of any expert system which uses the production rule technique of knowledge representation.

Multi-valued logic.

Again the two state classical logic approach is extended, but this time to include any number of possible states. For example, the possible states could range from definitely true through to definitely false with intermediate states such as possibly true, probably true, possibly false and probably false. The inclusion of these extra states requires that the normal logic qualifiers, such as AND and OR, are considerably modified to reflect the various levels of uncertainty allowed.

Fuzzy logic.

This technique is based on the fuzzy sets approach to incorporating uncertainty in reasoning logic. The approach is based on the assumption that truth can be measured on a scale from 0 to 1. For example, something which was known to be completely true would have a value of 1 associated with it, whereas something which was undoubtedly false would have the value 0. As uncertainty is introduced, the value of the indicator reduces to reflect the decrease in the level of confidence in the validity of the hypothesis.

3.5.1.1.2 Frame representations.

Rule based production systems can often comprise several hundreds of rules. Once a knowledge base becomes this large a number of problems can arise, such as those concerning control of the rule base and the relationships which exist between the rules. The inability to maintain control of the knowledge base can lead to new rules being added which either duplicate or contradict existing ones. Although some software tools are available to check a knowledge base for such conflicts or repetitions, the effec-

tiveness of the knowledge base is reduced because its originator loses awareness of the interaction between the various parameters represented in the rules. A secondary, and perhaps not so important consideration, is the fact that the size of the knowledge base can have a direct bearing on the speed of operation of the expert system. This arises due to much time being spent in the unnecessary processing of information as the size of the knowledge base increases.

An alternative to the production system is the frame representation, which allows hierarchical information about object relationships to be stored in a knowledge base. A frame is a knowlege structure which is used to hold information concerning the attributes of an object. The frame representation is fairly flexible in that each of the entries, or slots, can either be a single value for the attribute, a procedure to calculate the value, or a production rule to determine the value. An example of a frame representation is given in Figure 2.3.

It should be noted that a slot can contain multiple values for an attribute and that some slots, known as facets, are used to constrain the values which can be accepted as valid frame attributes, or the maximum and minimum number of values which can be assigned to an attribute.

Frames are organised on a hierarchical basis with the highest level frame containing information which is applicable to all frames below it, as illustrated in Figure 2.4. Although the lower frames are assumed to inherit the attributes of the higher level ones, these values can be over-ridden by the declaration of different values for the attributes in the lower frames, so allowing frames to easily handle exceptions. Procedures and production rules are also inherited from the higher level frames, but these too can be superceded at a local level.

Frame-based knowledge systems have several inherent advantages over the normal production system approach. For example, in the frame system, knowledge relationships are stored in addition to the knowledge itself, and storage space requirement is considerably reduced as attributes are stored only once at the highest level at which they apply. Another advantage of the frame representation, is that attributes can be evaluated using procedures or production rules thus enabling a very flexible knowledge structure to be derived. Perhaps the only disadvantage associated with this method of knowledge representation is the increased complexity of the inference mechanism

SHIP NAME	. .
CAPACITY	1500 TEU
SPEED	17 Knots
LENGTH	180.000 m
BREADTH	28.000 m
DEPTH	17.000 m
DRAFT	7.900 m
BLOCK COEFFICIENT	$\frac{\nabla}{L*B*T}$
POWER	9500 kW
ENGINE	4RND68M

OBJECT

ATTRIBUTES

Figure 2.3 Example of frame-based knowledge representation.

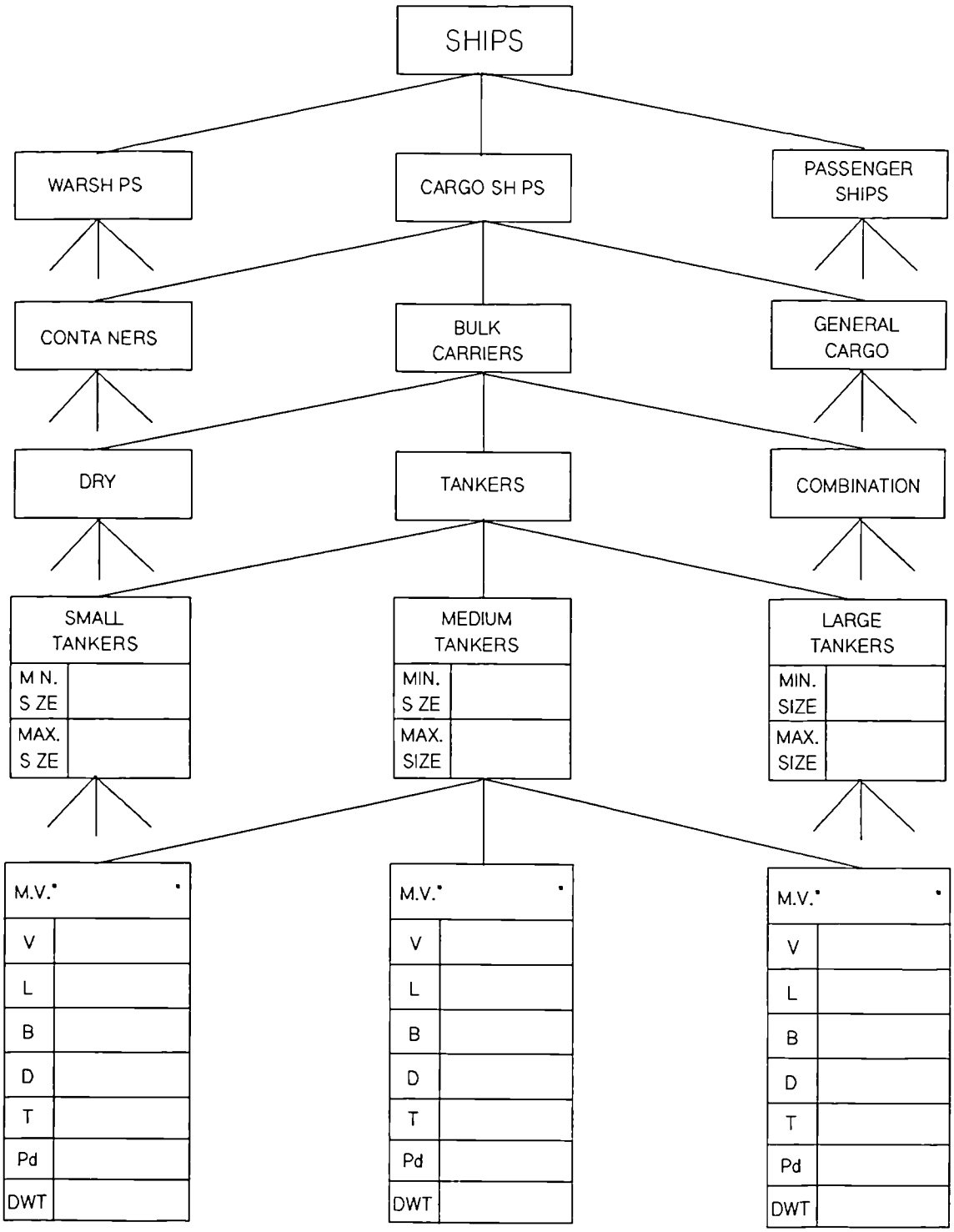

Figure 2.4 Example of a frame-based hierarchy.

required to control the logic.

3.5.1.1.3 Semantic networks.

The semantic network is perhaps the most general knowledge representation technique. In this representation scheme, the knowledge is expressed in terms of a network of nodes and links, where the nodes represent the objects and the links are the relationships between them. As with the frame representation, by using the semantic network scheme hierarchical relationships can be constructed, thus allowing nodes to inherit the properties of higher level nodes. Due to the similarities between the semantic network and frame-based representations, the two schemes tend to possess the same inherent advantages and disadvantages.

To illustrate the the application of semantic networks, Figure 2.5 shows a much simplified semantic network representation for marine propulsion devices. In the example, the objects represented by the nodes can be seen to comprise physical objects, categories and descriptors, but could also have been acts or events. The links, on the other hand, are the relationships between the objects, which, in the context of the example, can be seen to be *is a* (which indicates membership of a class), *has a* (which indicates that the object belongs to another node), and *property* (which indicates that the object possesses a certain characteristic). Two other types of link exist, those which indicate causal relationships, and those which indicate definitive relationships between the objects.

3.5.1.1.4 Predicate calculus.

This form of knowledge representation provides the basis for many of the computer languages from which expert system applications are derived, such as PROLOG [2.13] and POP-11 [2.14]. Predicate calculus consists of a formal language and syntax which are used to encode the knowledge and the relationships between the elements of knowledge. Basic predicate logic has only two values, true and false, which are known as boolean operators. The inability to handle quantified variables makes this type of propositional logic unsuitable for symbolic processing applications. In order to overcome this restriction, an extension of propositional logic, called predicate calculus, has been developed. This allows the expression of symbolic relationships between objects through the use of variables.

The syntax of predicate calculus is based on three types of symbol or atom; the con-

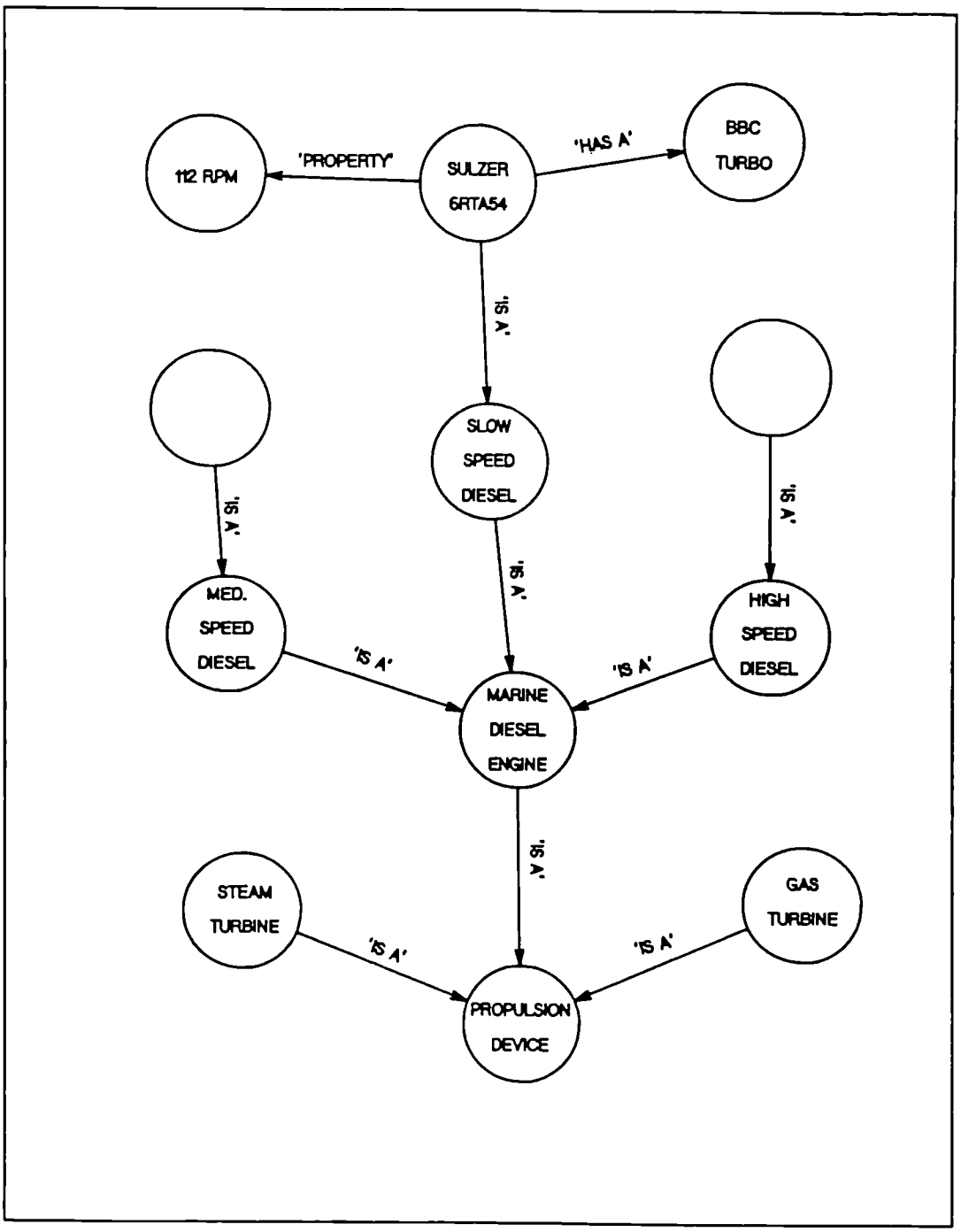

Figure 2.5 Example of a semantic network.

stant symbol, the function symbol and the relation symbol. The *constant symbol* is used to represent physical objects, while a *function symbol* is used to operate on an object in order that another object is returned. For example, *displacement* and *design speed* are both function symbols in that they would return objects (values) if they were to be applied to a constant symbol called *ship*. The final type of symbol, the *relation symbol* or *predicate symbol*, defines the relationship between various objects, for example :

diesel engine *is a* propulsion device

uses the predicate symbol *is a* to indicate the relationship between *diesel engine* and *propulsion device*.

In predicate calculus, propositions are defined using the three types of symbol described above in a statement called a term. These three types of symbol give rise to three types of propositions :

- the atomic proposition
- the logical proposition
- the quantified proposition.

The atomic proposition is concerned with the specification of constant symbols, while logical propositions are based on the logical operators such as AND, OR, NOT and IF. For example :

(NOT (is a *ship 1* **bulk carrier**))
(IF NOT (AND (*wing tanks*) (*hopper tanks*) **bulk carrier**))

is a proposition which involves the use of logical operators to indicate that *ship 1* cannot be a **bulk carrier** if it does not have *wing tanks* and *hopper tanks*.

A quantified proposition contains a quantifier such as ALL or EXISTS together with one or more variables, for example :

(ALL *x* (IF (**bulk carrier** *x*) (*ship x*)))

infers that all vessels of type **bulk carrier** are members of the class *ship*.

As mentioned above, this form of knowledge representation forms the basis of many

of the language systems which are used for the development of knowledge system applications. Some of these language systems will be described later.

3.5.2 The working memory or database.

The working memory of the expert system contains a set of parameters which represent the current situation and all of the attributes which have been established since the start of the consultation session. Obviously, the values of the parameters and attributes will change as the session progresses and more rules are invoked and more facts become known.

The working memory or database is the dynamic part of the knowledge base that changes with time.

3.5.3 The explanatory interface.

One of the main features of an expert system is that it can justify any conclusions drawn and explain any line of reasoning being taken. In order to gain the confidence of the user, this explanatory facility must be available at all times during the consultation. This enables the system user to appreciate the assumptions made in arriving at a particular conclusion and allows the structure and content of the knowledge base to be examined and verified. This feature is one of the aspects of the knowledge based system which sets it apart from normal procedural-type computer systems in which the logic is in-built and the assumptions and reasoning involved are not made apparent to the user. The explanatory interface also has an important function in that by explaining the current line of reasoning and justifying the assumptions made, it provides the user with the opportunity to either agree with the conclusions and recommendations made by the system, or to contradict them and impose his own requirements. This ensures that the user remains in overall control of the session and has the power to drive the session in the direction required.

3.5.4 The natural language interface.

In order that the user can communicate with the computer system and vice versa, some form of natural language interface must be incorporated into the system to provide the vehicle for input and output. At present, most knowledge based systems use a very primitive interface which restricts the user to communicating with the system via a

small set of pre-defined symbols which it can recognise and act upon. It is eventually hoped that users will be able to communicate with computer systems using instructions expressed in complete natural language sentences.

Most expert systems use a set of symbolic instructions which is limited to basic commands such as yes, no, why, how etc. Some of the more complex systems are able to perform simple parsing (the building up of sentences from component parts) to develop comprehensible instructions, although such systems are currently few and far between.

Despite the limitations imposed by small instruction sets, the natural language interface provides a user-friendly vehicle for user/machine interaction which contributes towards encouraging the user to exploit the full problem solving potential of the knowledge based system.

3.5.5 The inference engine or rule interpreter.

The inference engine or rule interpreter performs two main tasks. Firstly, it examines the existing facts in the working memory and the rules in the rule base and adds new facts to the working memory whenever possible. Secondly, it determines in which order the rules contained in the rule base are to be examined and fired. The inference engine also keeps the system user informed as to the progress being made and prompts him for further input when no further rules can be invoked or facts determined.

The inference engine can employ one of two methods of reasoning, backward chaining or forward chaining. A backward chaining system attempts to find support for particular conclusions supplied by the user or obtained from the working memory, by looking at a number of conclusions in turn. Forward chaining involves the inference engine using the available rule in the rule base to produce facts which will eventually lead to a conclusion. These two approaches are shown diagramatically in Figure 2.6.

The inference engine can be considered to comprise two parts, the inference component and the control component. The task of the inference component is to examine the rules and the working memory and to update the working memory whenever possible. The control component is designed to determine the order of firing of the rules contained in the rule base.

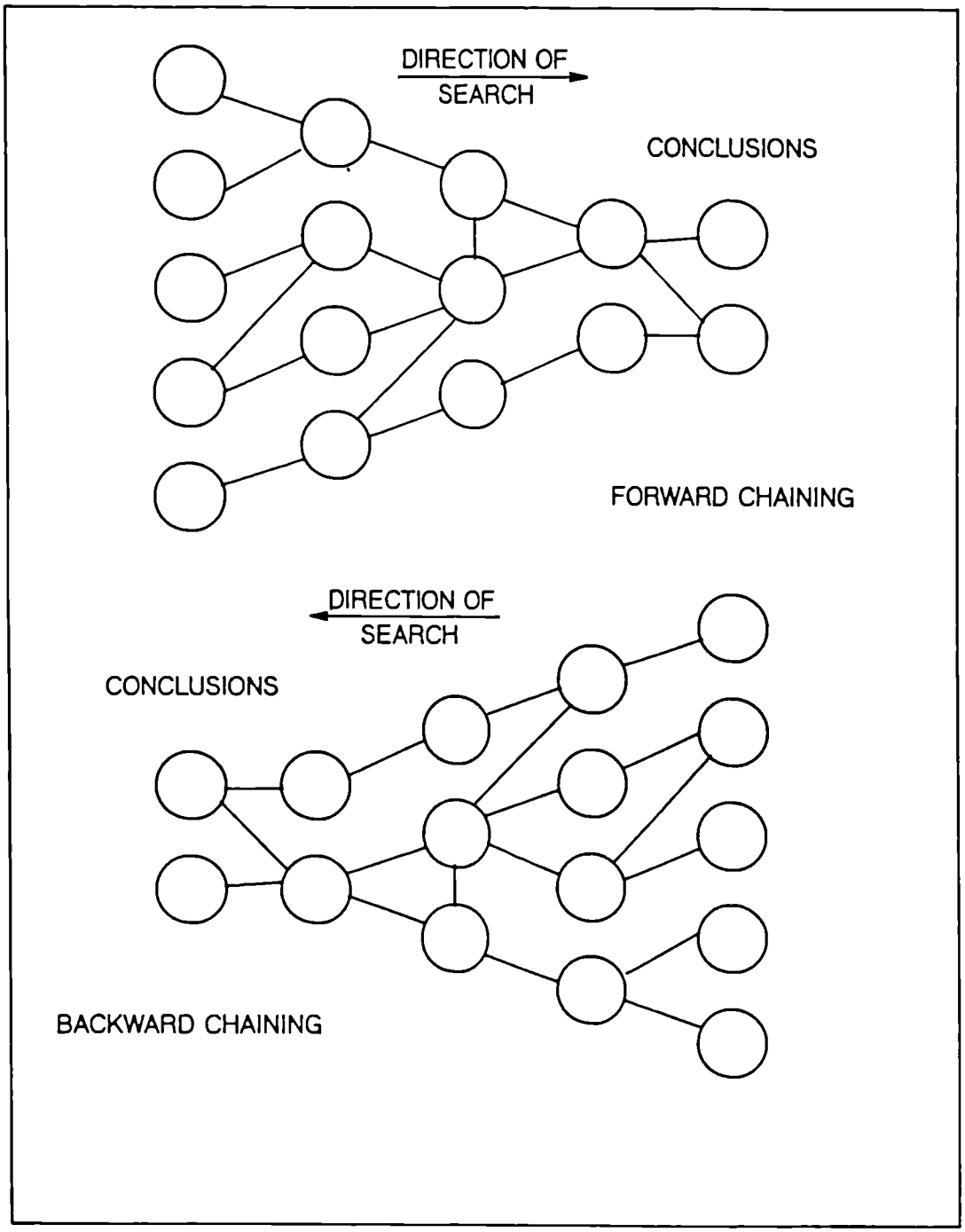

Figure 2.6 The forward and backward chaining inferencing techniques.

3.5.5.1 The inference component.

This part of the inference engine works on the simple assumption that if the premise of a rule is true then the associated conclusion must also be true. By the constant application of this assumption to the rules in the rule base more and more facts become known and so the working memory is continually updated. One feature of the inference component is its ability to work with incomplete information, a factor which contributes towards making an expert system vastly different from normal computer systems. For example, a system user may be unable to respond positively to a particular prompt from the expert system and so have to reply with the equivalent of unknown. The inference component will have to be able to side step this particular area of the knowledge base and try a different approach. Normal computer systems would come to an abrupt halt if the user was unable to supply a piece of information asked for by the system.

3.5.5.2 The control component.

The control component of an inference engine has four main functions :

1. Matching; it matches the pattern of rules against the pattern of known facts.

2. Selection; it determines the most relevant rule to fire based in the currently known facts, ie. conflict resolution.

3. Firing; rules are fired when antecedents are satisfied.

4. Action; the working memory or database is updated and the conclusion added to the known facts. An output may be initiated.

The control component usually works in cycles, scanning existing rules to see which ones have premises which match the known facts in the working memory and firing them when required. As only a single rule can be fired in each cycle, some method of deciding which one to invoke must be used if more than one rule matches the available facts. The control component is also able to determine which of the rules can be invoked according to the current state of facts in the working memory and hold these

rules in the conflict set. The control component, depending on which control strategy it has been based, then selects one rule from this conflict set and fires it to create a new fact which can be added to the working memory, thus enabling the whole process to be repeated. The nature of this control cycle is shown in Figure 2.7.

The design of the control component of an inference engine largely depends on which method which has been chosen for searching through the rules and firing them. These are a number of general techniques which are used to search rule bases and invoke rules, such as the depth-first search method, the breadth- first method, problem reduction, the alpha-beta algorithms, and generate and test.

The depth-first and breadth-first searching techniques, as shown in Figure 2.8, are basically similar in their approach and so are usually considered together. The depth-first search involves following a single line of reasoning until it is exhausted and either a conclusion has been reached or a dead-end has been encountered. The breadth-first search involves exploring all avenues down to a particular level before proceeding to the next level of detail.

The depth-first approach is often preferred over the breadth-first as all of the information relating from a particular line of reasoning will be presented together, whereas the information flow from a breadth-first search will tend to be confused as the line of reasoning is constantly being changed. One advantage the breadth-first search has over the depth-first approach is the usually shorter time taken to reach a conclusion. This occurs because the depth-first search may involve following a number of lines of reasoning to unsuccessful conclusions, whereas the breadth-first search may experience success at a quite low level of detail, after considering only a few rules.

Problem reduction involves specification of the overall problem in terms of sub-problems which the control component attempts to solve. As these sub-problems are solved, large areas of the search space become redundant, therefore greatly reducing the number of steps required to reach an overall conclusion. The only major drawback with this approach is considerable planning effort required in order that the knowledge base is correctly structured in terms of a hierarchy of goals and sub-goals. Failure to structure the knowledge in such a way can lead to a very large increase in the number of steps required to achieve the overall goal.

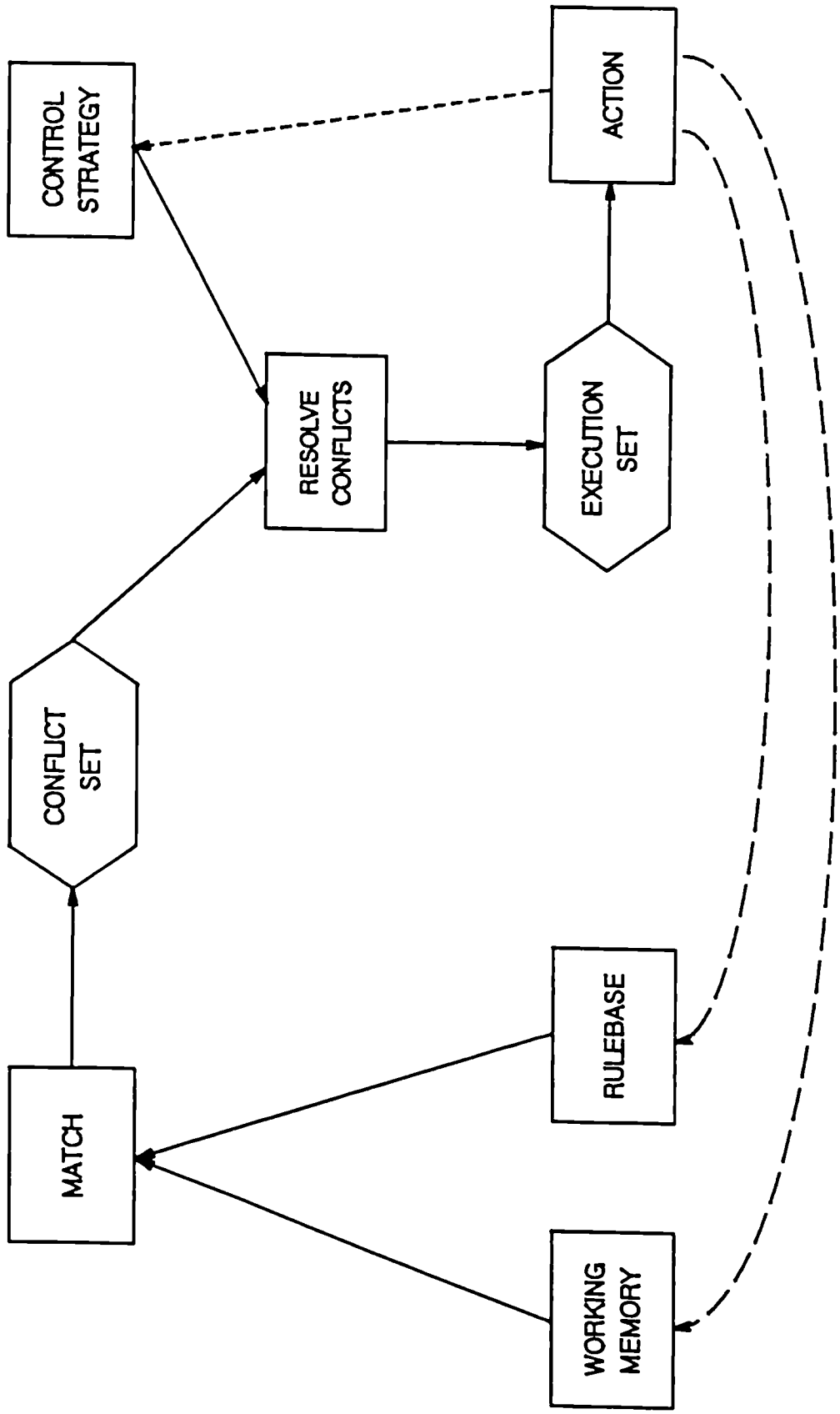

Figure 2.7 The expert system control cycle.

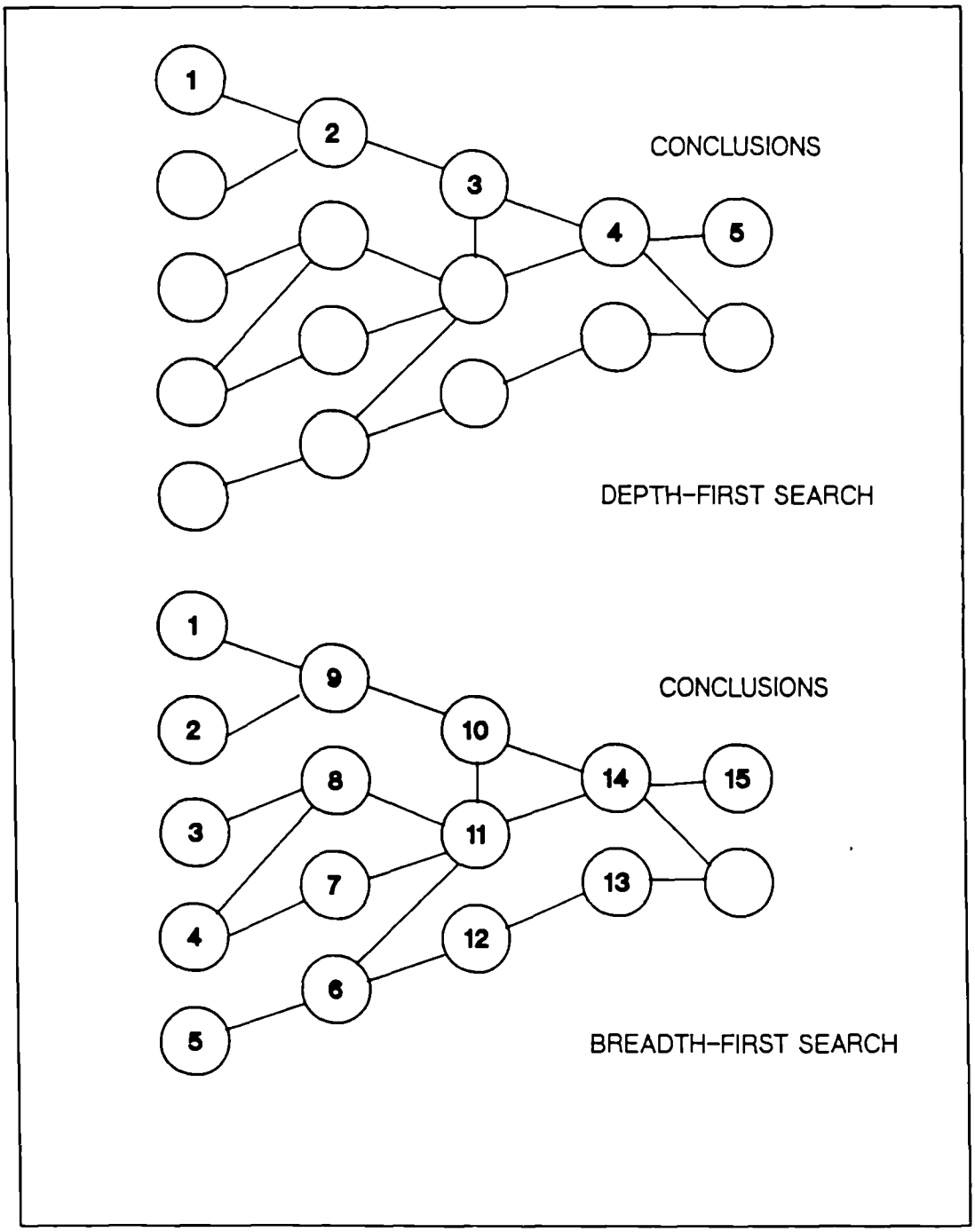

Figure 2.8 Depth-first and breadth-first search techniques.

The alpha-beta algorithm attempts to reduce the size of the search space by cutting off branches of the space which need not be evaluated. This involves checking nodes at the next detail level to see if the particular line of reasoning is redundant due to a fact previously established. This technique is often used to improve considerably the efficiency of the search process in expert system applications.

Another, less reliable technique, is the one whereby heuristics are used to influence the search and guide it towards the best possible solution.

One shortcoming shared by all of the above search techniques is the possibility that non-optimal solutions may be found. All of the techniques will usually result in the search being terminated upon finding a single solution, with some of the techniques being more likely to discover non-optimal solutions than others. For example, the depth-first search method will usually discover a solution which is non-optimal as it persists along a single line of reasoning without regard for external factors which may indicate a better solution is to be found along a different path. Unfortunately, the only method available of ensuring that the best solution is found every time is to follow every line of reasoning until all of the feasible solutions have been found. This generate and test technique can be applied successfully to those applications where only a few solutions are known to exist, but in most cases the time and effort required to check every possible solution to a problem makes the technique impractical.

3.6 Expert System Tools.

The previous sections have described in some detail the advantages of adopting a knowledge based system approach to problem solving and also the techniques which can be enlisted to represent and reason with knowledge.

There are a number of ways in which these techniques can be applied to the development of practical problem solving systems. The software tools used to implement knowledge based systems usually fall into one of three categories, namely languages, toolkits and shells.

3.6.1 Languages.

An expert system can be written in almost any high level language such as C, Pascal, FORTRAN, and Modula-2, but those languages which permit symbolic processing such

as PROLOG, LISP, POP-11 and Forth, are usually preferred. One of the main drawbacks of using symbolic processing languages is that they are usually interpretive and as such the speed of execution of applications written using them is very low. However, considerable effort is currently being put into the development of compilers which will greatly enhance the use of symbolic processing languages as a means of developing knowledge based system applications.

There are a number of development tools available which provide a total artificial intelligence environment including editors, incremental compilers and multi-language processing. One such system, POPLOG [2.15], offers three symbolic processing languages which can be combined in a single AI application. These three languages, PROLOG, common LISP and POP-11, can also be combined with procedural-type routines written in languages such as FORTRAN and Pascal. With the addition of a full context editor, VED [2.16], POPLOG provides a very flexible development tool for knowledge based system applications.

3.6.2 Toolkits.

Toolkits provide a highly flexible aid for the development of knowledge based system applications. Toolkits usually provide a symbolic language processing capability together with context editors, in a package which includes a number of software tools such as forward and backward chaining control strategies, data capture and processing modules, and frame-based knowledge representation procedures. The highly user-friendly nature of these systems means that applications are generally very easy to develop and maintain. Typical of this type of development aid are the MUSE AI toolkit from Cambridge Consultants Limited [2.17] and the Inference ART toolkit from Ferranti Computer Systems Limited [2.18].

These toolkits combine the best features of the available knowledge based system techniques and put them in a highly flexible package, allowing the most suitable knowledge representation techniques and inference control strategies to be selected for particular applications. Toolkits are often used for the development of real-time expert system applications such as those associated with plant monitoring and control and fault diagnosis ([2.19], [2.20], [2.21].

3.6.3 Expert system shells.

Expert system shells form the basis for many production systems. At first sight, this class of development tool appears to offer a considerable number of advantages over the two already mentioned. A shell is a ready made expert system without the knowledge base. It comprises the inference engine, the explanation interface and the user interface. The availability of such shells can considerably reduce the time taken to develop knowledge based system applications provided that the correct shell is chosen in the first instance. By adopting a shell the knowledge engineer does not have to concern himself with the mechanics of inferencing, natural language processing, etc., but can simply concentrate on developing the knowledge base for the solution of his particular problem. In selecting expert system shells, the knowledge engineer must consider the type and number of rules which are likely to be used, the type of inferencing which is required and the nature of the user interface which he desires, as he will have virtually no control over these aspects of the shell which he finally selects.

A large number of commercial shells are available, written in a wide range of computer languages. These shells vary considerably in the complexity and flexiblility of their operation, making the task of selecting the correct one for a particular application very difficult. The suitability of a shell for a particular application will usually be dependent on which techniques the shell uses to represent and reason with knowledge. One of the better known shells is CRYSTAL, from Intelligent Environments, one which has received considerable attention since its introduction in 1987 ([2.22], [2.23]). Some shells allow considerable flexibility in handling data input from sources other than the system user, a feature which is obviously of considerable importance to anyone developing any kind of monitoring or control system.

A critical review of many of the currently available expert system shells can be found in [2.24].

4. The suitability of the proposed application.

Upon close examination of the proposed application, that is the conceptual ship design system, it would appear that expert systems could provide the features required to form the basis of the system. Expert systems provide the ability to develop flexible computer-based systems which incorporate the heuristic and rule based knowledge

associated with the ship design process. The number and scope of the expert system based engineering design applications currently in use or under development would appear to confirm that this approach does have considerable advantages to offer in the area of engineering design.

It now only remains to assess the requirements of the proposed application and determine which of the available expert system development techniques would appear to be most suited to being the basis of a system for the conceptual design of ships.

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CHAPTER 3

The INCODES Expert System Shell.

SUMMARY.

This Chapter discusses the reasons for adopting an expert system shell approach to the development of the conceptual ship design system. The reasons for deciding to develop a unique expert system shell which has FORTRAN 77 as its base language are discussed in detail. The components of the expert system shell are described as are the various features of the shell which contribute towards making it ideally suited to the development of engineering design applications in general, and the conceptual ship design system in particular.

1. Introduction.

Having decided that a knowledge based system approach was to be adopted for the conceptual ship design system, the next task was to determine which of the available techniques would provide the most suitable basis for the system. As mentioned in the previous Chapter, the choice of software tool for the development of knowledge based systems lies between languages/environments, toolkits and shells.

Toolkits offer considerable flexibility to the knowledge engineer in that they permit the use of most of the available knowledge representation techniques, together with the usual inference mechanisms, as well as permitting interfacing with routines written in procedural-type languages. This type of development tool would therefore appear, at first sight, to provide the obvious answer to someone looking for an expert system development aid. This hypothesis would be true if it was not for one thing, the cost. Toolkits are by far the most expensive software tools available for the development of artificial intelligence applications. Their very high cost makes them totally inaccessible to all except those who have a very strong commitment to the develop-

ment of knowledge based problem-solving systems.

Languages such as Prolog, Lisp and Pop-11, either when used as part of an environment or simply as stand alone compilers/interpreters, provide the means for the manipulation of symbolic information held in user created databases. This object-oriented approach provides access to the considerable power of communication by means of symbolic representation, but to those who are used to dealing with knowledge in terms of numerical and mathematical modelling using procedural-type programming languages, the use of such declarative programming techniques may present some quite significant problems. Most engineering problems are solved using a procedural approach based on language packages such as FORTRAN or Pascal. The declarative style of programming provides the engineer with a considerable challenge, not only by being associated with unfamiliar programming languages with their accompanying syntax and structure problems, but also because not all engineering problems can be represented in symbolic terms. Many engineering decisions are based purely on numerical information and complex mathematical models of physical problems. The solution or evaluation of such models using computer based methods relies on the fact that the programming languages being used provide all of the necessary mathematical and scientific functions. Unfortunately, symbolic processing languages do not support the full range of mathematical and scientific functions which are to be found in nearly all procedural-type languages. They are therefore largely unsuitable for applications which involve a significant amount of numerical processing.

An additional problem associated with symbolic processing based languages, is their inability to interface easily with graphical procedures. For many knowledge based system applications, the provision of a means of producing graphical output is not too important, but in a system which is to provide support and guidance in the area of engineering design this feature is considered to be a necessity rather than a luxury. To overcome this problem, there has recently been some movement towards the implementation of a Prolog based version of the GKS (Graphical Kernel System) graphics standard ([3.1], [3.2], [3.3]), but as yet most of the available implementations of the language do not provide a graphical capability.

The speed of execution of symbolic processing languages is also a problem as the available implementations of the languages are normally of an interpretive rather than a compiling nature. This slow execution speed is not too important for systems which

involve only a small number of rules, but for systems which incorporate large knowledge bases the speed of execution could have a highly detrimental effect on the apparent quality of the system. The introduction of compiling versions of the languages will obviously go some way towards solving the problem of execution speed, but it is doubtful whether symbolic processing languages could ever match the performance of procedural-type languages in this respect.

Expert system shells allow the rapid development and implementation of expert systems due to the inference engine and the various interfaces already being provided. This means that the system developer need only concern himself with formulating rules and creating the knowledge base relevant to his particular problem domain. Although shells are written such that they can incorporate any knowledge base that the user wishes, each of the available shells will obviously be more suited to certain types of application than others, as illustrated by a survey of shells for construction industry applications [3.4].

One major advantage of expert system shells is the special languages used by them to encode the knowledge. The use of these special knowledge representation languages (KRL) means that the knowledge base creator does not have to use abstract declarative programming techniques normally associated with the symbolic processing languages. Knowledge representation languages allow rules and other domain related knowledge to be expressed in a near-natural language format, therefore avoiding the problems associated with the syntax and structure of the languages, such as Prolog and Lisp, on which the shells are based. The task of translating knowledge representation language statements into their symbolic processing equivalents, for use by the base language, is carried out by the knowledge representation language compiler, which is an integral part of every system shell, as illustrated in Figure 3.1. This provides the user with a friendly transparent interface to the base language of the shell.

Despite a knowledge representation language being much more user-friendly than the symbolic processing language into which it is eventually translated, it can only offer the same basic features as the host language. Therefore, an expert system shell which has Prolog as its base language, for example, can only offer a knowledge representation language which has the same restrictions on mathematical and scientific functions and graphical representation as the Prolog language itself. The dependance of expert system shells on the features and limitations on their host languages can therefore be

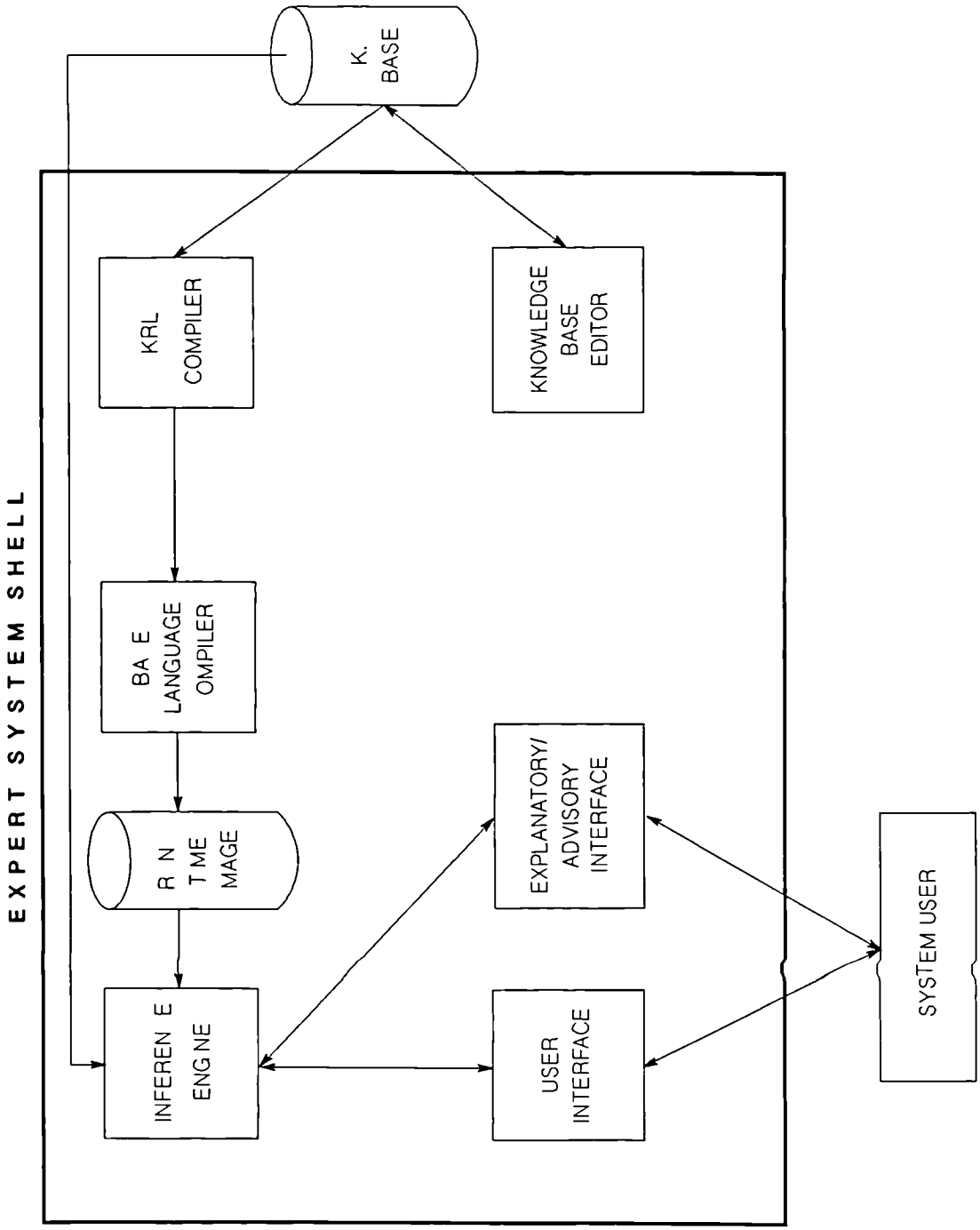

Figure 3.1 Structure of a typical expert system shell.

a major disadvantage in many cases.

All current expert system shells impose a restriction on the size of knowledge base which can be attached. A limitation of a maximum of a few hundred rules may not be significant in most applications, but it may be a severe restriction in some cases where a fairly complex problem is being considered.

Once again, the speed of operation of shell-based expert system applications tends to be relatively slow, this being of course due to the shells usual reliance on a symbolic processing type of host language.

Despite the disadvantages associated with the use of expert system shells, the flexibility that they offer together with their cost-effectiveness and the relative ease with which their respective knowledge representation languages can be used to create knowledge bases, makes them the most convenient means of developing knowledge based systems available. For the conceptual ship design system being considered here, it was therefore decided to adopt a shell approach to building the knowledge based part of the system. In view of the limitations associated with currently available commercial shells in respect of their mathematical, scientific and graphical capabilities, a decision was made to develop a shell specifically for the ship design system using the accepted engineering programming language, FORTRAN 77, as the host language.

2. Requirements of the concept ship design system shell.

The INCODES (INtelligent COncept DEsign System) expert system shell [3.5], as it became known, was developed according to a number of specific requirements as indicated below:

- The shell was to be written in FORTRAN 77 to make development and maintenance of the shell itself a fairly simple task.

- The shell was to allow direct access to external analysis procedures written in procedural-type languages such as FORTRAN 77, Pascal and C.

- A graphical capability was to be provided as this was considered essential for a system which was to offer advice and guidance in the area of engineering design.

- The shell was to support the full range of mathematical and scientific functions provided by the FORTRAN 77 programming language.

- The shell was to incorporate a knowledge representation language which would allow the system user to create a knowledge base using pseudo-English statements. The structure and syntax of the language would be such that non-programming personnel would be able to construct quite complex knowledge bases with relative ease in a fairly short time.

- The full range of data types and structures found in FORTRAN 77 would be supported in the knowledge representation language.

- The size of the knowledge base would not be restricted in any real sense, that is, the shell had to be capable of handling an engineering application of a fairly complex nature which might involve several hundred rules.

- The user interface was to permit the user to communicate easily with the system. A set of near-natural language commands were to allow the user to interrogate the knowledge base, apply constraints, question reasoning and so on.

- The knowledge representation language was to be able to represent adequately the heuristic knowledge associated with the ship design process.

3. Components of the shell.

In view of the basic requirements for the shell which have been described in section 2 above, an outline of the main components of the shell was produced as indicated in Figure 3.2. From this diagram the shell can be seen to comprise seven main elements, as indicated below:

- The knowledge base editor.
- Knowledge base compiler.
- FORTRAN 77 compiler.

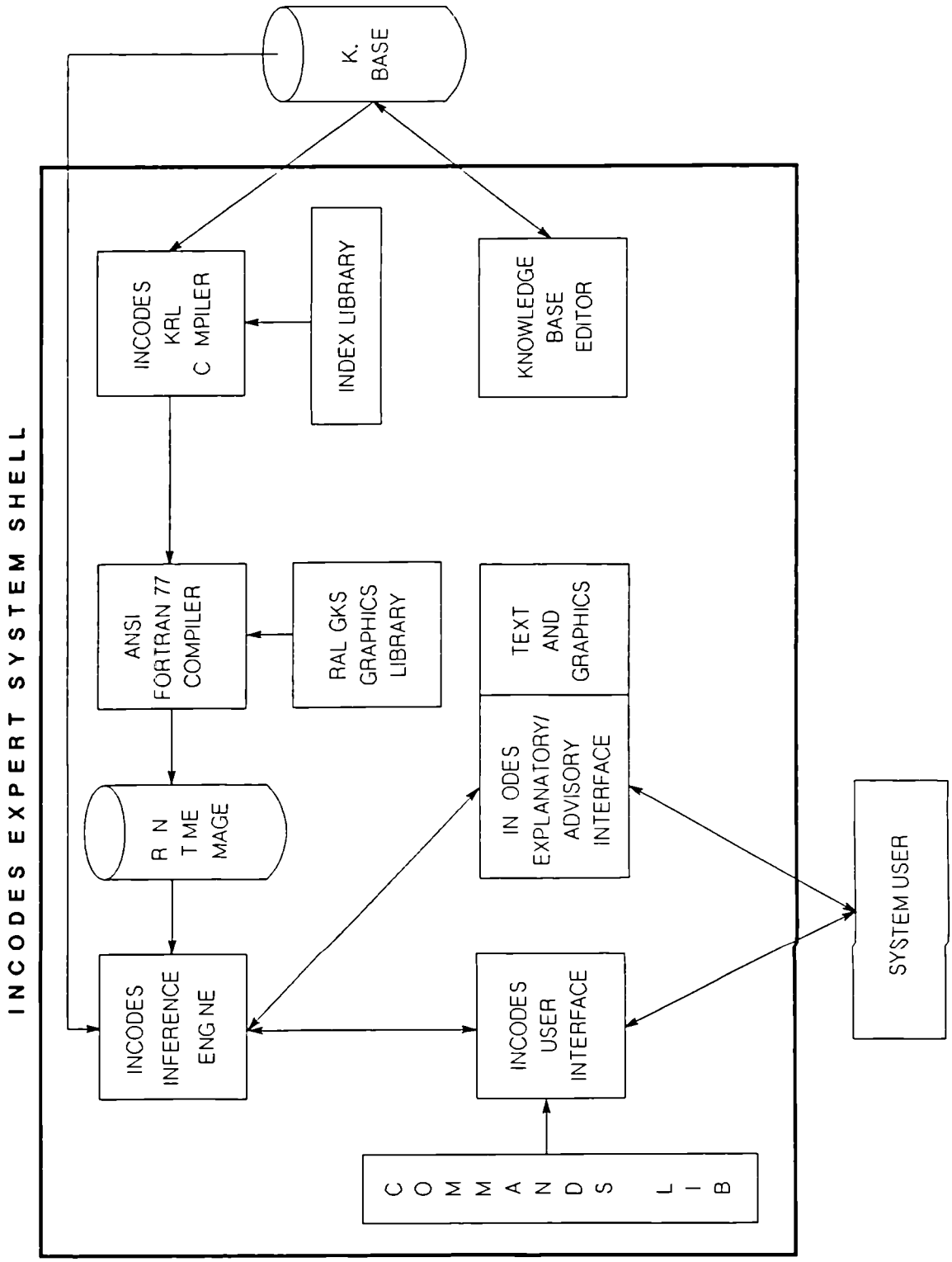

Figure 3.2 Structure of the INCODES expert system shell.

- Inference engine.
- User interface.
- Explanatory/advisory interface.
- Graphics primitives library.

Components of the shell such as the FORTRAN 77 compiler, knowledge base editor and the graphics primitives library, although vital parts of it, were not developed specifically to form part of the system, but were obtained from a variety of third-party sources. The FORTRAN 77 compiler, for example, is an ANSI standard compiler developed by SUN Microsystems [3.6] with extensions to permit compatibility with VAX/VMS FORTRAN 77 [3.7]. Similarly, the knowledge base editor is taken from the operating environment of the SUN 3 workstation on which the system is based, although in practice, any standard text editor could be utilised to create knowledge base source files in standard ASCII format.

The graphics primitives library utilised by the shell is also a software package produced externally which was adopted for use in the system. The GKS (Graphical Kernel System) graphics library [3.8] was selected due to the fact that it is the accepted international standard for 2-dimensional graphical representation. The particular version of GKS utilised was developed by the Rutherford Appleton Laboratory of the Science and Engineering Research Council [3.9]. The Graphical Kernel System covers the most significant parts of the area of generative computer graphics, and is the first international standard for programming computer graphics applications. In short, it provides functions for picture generation, picture presentation, segmentation, transformations and input.

Those parts of the shell which were specifically developed by the author for inclusion in the system, are the knowledge base compiler, the inference engine, the user interface and the explanatory/advisory interface.

3.1 The knowledge base compiler.

The basic task of a knowledge base compiler is to translate the information contained in the knowledge base from the format of the knowledge representation language into the base language of the expert system. In this case, the INCODES knowledge base compiler was developed in order that the knowledge representation language state-

ments held in the knowledge base could be translated into valid FORTRAN 77 statements, which could then be compiled by the FORTRAN 77 compiler. These compiled FORTRAN statements could then used by the inference engine to invoke rules and create facts which could be added to the working memory during a consultation.

Before considering the knowledge base compiler in any detail, it is first necessary to examine the INCODES knowledge representation language which was developed for use in knowledge base creation.

3.1.1 The INCODES knowledge representation language.

The main requirement of any knowledge representation language is that it must be capable of adequately representing the types of knowledge associated with the problem domain under consideration. It must also be fairly easy to use, with the structure and format of the language being such that knowledge bases are easy to read and understand. When considering the requirements of a language which could adequately represent the knowledge associated with the conceptual design of ships, a number of important aspects were identified which required careful consideration. These points were concerned with the way in which the knowledge to be found in conceptual ship design is represented. Monaghan [3.10] proposed that the knowledge associated with the conceptual design process could be categorised as follows:

- Domain knowledge: Knowledge about sub-systems and components. Domain knowledge is classified in terms of a hierarchy of subsystems and components into which successive levels of detail are introduced. Heuristic search techniques are adopted for exploration of the design space.

- Constraint knowledge: Constraints applied by standards and regulations. These describe the requirements of regulatory bodies which must be satisfied in the final design proposal.

- Procedural knowledge: Knowledge of the design process. The fundamental activity of the conceptual design process is the identification and application of constraints. These constraints cannot be applied in isolation as their nature will be influenced by the current

state of the developing proposal.

- Analysis algorithms: Knowledge of how to evaluate and analyse developing and final proposals. The analysis algorithms are used to analyse, evaluate and compare the performance of the developing and final proposals against the specified requirements.

- Proposal knowledge: Knowledge of the developing proposal. Graphical and textural descriptions are used to represent the developing proposal.

An examination of the above types of knowledge showed that they were likely to be encountered in the conceptual ship design process. It was therefore concluded that any knowledge representation language intended for inclusion in an expert system shell aimed at the conceptual ship design process had to possess a syntax and structure capable of supporting the above types of knowledge.

3.1.2 Structure of the INCODES knowledge representation language.

Domain knowledge and constraint knowledge can usually be specified in terms of a series of production rules of the IF..THEN antecedent and conclusion construct, a fact which resulted in the production rule approach being adopted for the INCODES shell. By using such a representation, the heuristic knowledge associated with concept design and the constraints imposed by classification societies and other regulatory bodies could be accommodated. In order that the knowledge representation language could be developed, the various of forms of production rule which could possibly be encountered had to be considered.

In its most basic form, a typical production rule could look something like:

IF (qualification) THEN (conclusion)

This example illustrates the use of IF and THEN as logical qualifiers. Obviously the example indicates that there is only a single qualification in order for the conclusion to be true, whereas in reality multiple qualifications will occur, such as:

IF ((qualification) AND (qualification)) THEN (conclusion)

This production rule has introduced the logical qualifier AND, which indicates that both of the qualifying statements have to be satisfied before the conclusion can be reached. Similarly, the logical operator OR could have been used which would have meant that only one of the two qualifications needed to be satisfied in order that the conclusion could be reached. An extension to the exclusive use of the AND and OR logical qualifiers, is the type of production rule where individual logical qualifiers are combined to give a quite complex overall qualification, as indicated below:

IF (((qualification) AND (qualification)) OR
((qualification) AND (qualification)) AND (qualification)))
THEN (conclusion)

The above example suggests that the qualifications can be grouped with the conclusion being reached if all of the qualifications in any of the groups are satisfied.

An extension of this concept involves the introduction of the ELSE statement which indicates that a conclusion will always be forthcoming even if the preceeding qualifications are not satisfied, for example:

IF (((qualification) AND (qualification)) OR (qualification))
THEN (conclusion)
ELSE (conclusion)

The ability of a knowledge representation language to represent knowledge expressed in terms of production rules, *requires that the set of logical operators and qualifiers* IF, AND, OR, THEN and ELSE are supported by the language syntax. The knowledge representation language developed by the author to form the basis of the INCODES shell, does indeed provide these operators and qualifiers in its support of the production rule knowledge representation technique.

Apart from logical qualifiers, the production rule contains two other types of statement, the qualification and the conclusion. These statements are those parts of the rule which contain the symbolic information, that is, the parameters or variables with which the rule is concerned. In the context of a ship design system, the symbols could represent physical objects (such as main engine, hatch cover, deck crane, etc.), object properties (mass, dimension, speed, etc.) and relationships between objects (is a, has a, etc.). For example, the rule:

IF (*cargo handling gear type* is *single pedestal*)
THEN (*lifting capacity* is 35.0 tonnes)

introduces symbolic information into the production rule schema.

The symbols used in engineering design can normally be placed into three main classes, those which are associated with numerical values, those which are associated with textural values, and those which have boolean values. These three categories can be further subdivided as shown in Figure 3.3.

It is possible for a single type of symbol to take on values associated with any of the three groups defined above. For example, the following statement:

cargo handling gear type is *gantry crane*

suggests that the symbol *cargo handling gear* is of type *property*, and has the character string value *gantry crane*. Similarly, the following:

design speed is *17 knots*

suggests that the symbol *design speed* is also a property symbol but this time has a numerical value, and finally :

cargo handling gear fitted is *true*

involves the property symbol *cargo handling gear fitted* but this time with the boolean value *true*.

The connections between the symbols are indicated by statements such as *is*, *equal to*, *not equal to*, *less than* and so on. These connective statements complete the qualification part of the production rule, and can also be found in the rule conclusion, as shown in the following example:

IF (.....) THEN (..... is .....)

The knowledge representation language developed for the INCODES shell provides the user with the three classes of symbol described above. These can be used together with a comprehensive set of connective statements and the logical qualifiers and op-

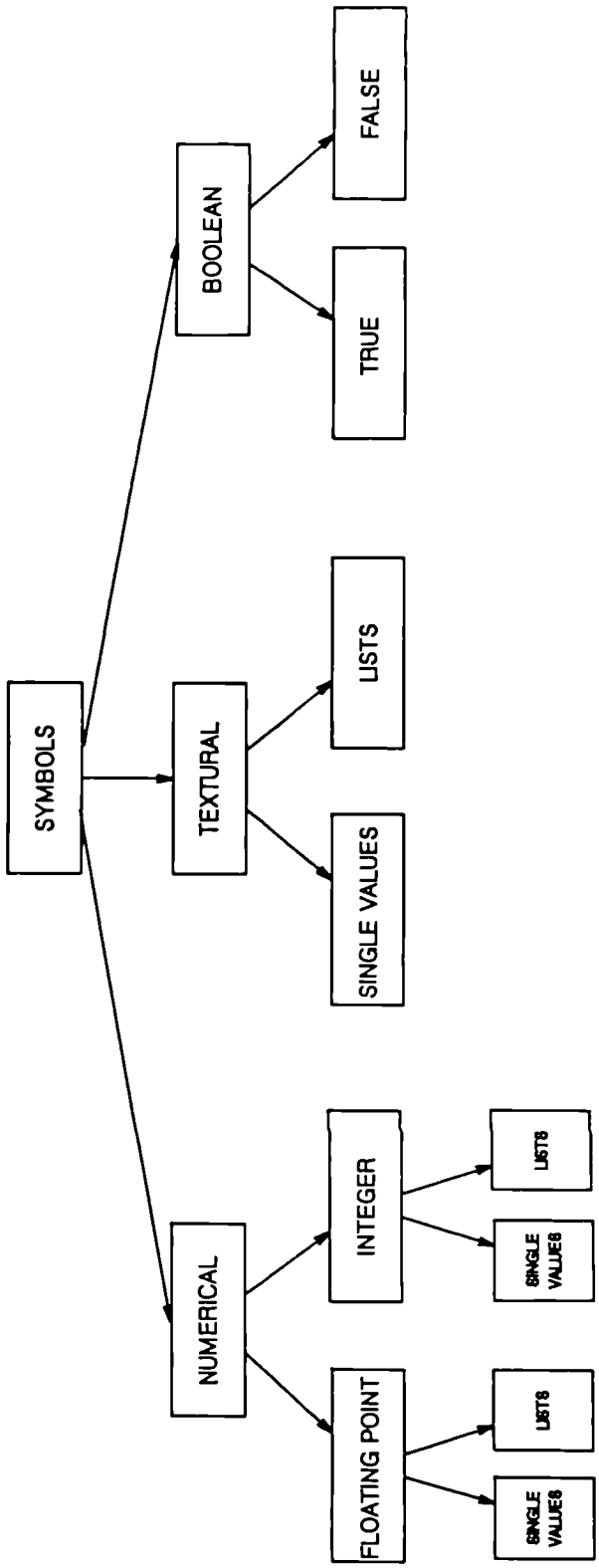

Figure 3.3 The available symbol types within INCODES.

erators supplied, to represent the heuristic and factual knowledge associated with the problem domain of conceptual ship design.

As mentioned previously, the ability of an expert system shell to access external analysis routines is considered essential if it is to be used effectively for the development of engineering design applications. The knowledge representation language of the INCODES shell was developed to allow direct access to external routines written in many high level languages. Communication with these external procedures is via input and output datafiles which are specified in the knowledge base. The knowledge representation language allows for the specification of the contents of these communication files in terms of their symbolic content. A typical communication file might consist of various symbolic information, numerical, textural and boolean, which is written in a specific format as indicated in the knowledge base. Similarly, symbolic information which results from the execution of an external procedure can be read from output datafiles in the format specified in the knowledge base. In such cases, the results from the external procedure may be of no particular interest to the working memory of the system and may only be required by another external procedure. In this case the knowledge base will not contain information relating to the actual symbolic content of the communication files as these will be considered as *black boxes* without any knowledge of their significance. This feature allows massive amounts of data, which have no significance as individual items, to be processed by the system with comparative ease. The inference engine of the shell is made aware of the existance of these data-sets in the knowledge base and and can therefore pass them between external routines without ever being aware of their exact contents. In the context of the containership design system being described here, for example, a communication file could contain information relating to the exact locations of all of the containers which can be accommodated on a particular vessel. This information, although vital to the operation of the system as a whole, is not required explicitly by the inference mechanism and can therefore be considered as a black box, and as such, passed around the various procedures which need the relevant data.

In any expert system, facts can be defined by the system user as well as by rules and external procedures. The information required from the user will usually be in the form of the design requirements specification which is to be used as the initial starting point for the investigation.

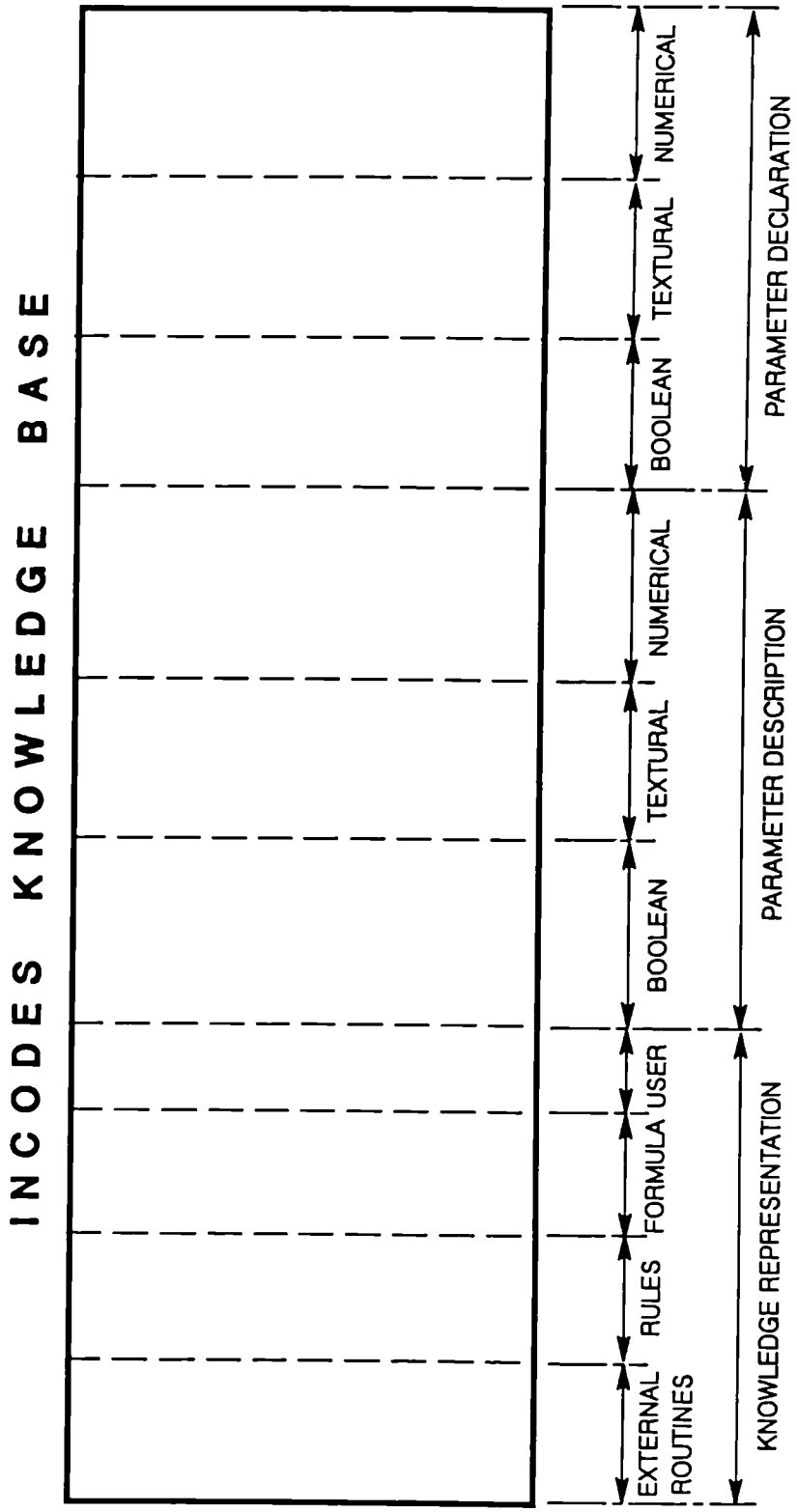

Figure 3.4 Structure of an INCODES knowledge base.

3.1.3 Syntax of the INCODES knowledge representation language.

It is obvious that any computer language must have a syntax associated with it. The syntax developed for the knowledge representation language of the INCODES system was designed to offer considerable flexibility, while remaining sufficiently structured so as to avoid large numbers of errors during knowledge base creation. Upon examination of the information to be stored in an INCODES knowledge base, a number of specific knowledge groups were identified. This breaking down of the knowledge base into discrete areas enabled a general knowledge base structure to be proposed, as shown in Figure 3.4. As can be seen from the diagram, the knowledge base is divided into three basic areas:

- parameter declaration
- parameter description
- knowledge representation

with these areas being further divided into smaller sub-groups.

3.1.3.1 Parameter declaration.

The parameter declaration part of the knowledge base, as the title suggests, is concerned with the categorisation of the parameters or symbols according to their types, as indicated in Figure 3.3. This identification of symbol types is necessary for the successful compilation of the knowledge base into FORTRAN equivalent statements, and it also has the effect of forcing the knowledge base creator to consider the context of the symbols being utilised and the values that they may possibly take on during the course of a consultation. Figure 3.5 shows a typical section of knowledge base covering the declaration of symbol types.

3.1.3.2 Parameter description.

Parameter descriptions are vital if an expert system is going to be able to assist the user in his efforts to provide required input data, and also provide explanations of assumptions made and lines of reasoning followed. The information contained in the parameter descriptions can be accessed by the expert system when required to do so by the system user. An example of the parameter description section of knowledge base is shown in Figure 3.6.

```
    T Y P E   D E C L A R A T I O N
!   -------------------------------

  REAL : 'DEPTH_TO_FREEBOARD_DECK' 'DEPTH_TO_SECOND_DECK' 'DEPTH_TO_UPPER_DECK'
++       'HEIGHT_OF_ENCLOSED_SS' 'TOTAL_VCG' 'TOTAL_LCG' 'MAX_PERMISSIBLE_VCG'
++       'ACTUAL_WHM' 'MAX_PERMISSIBLE_WHM' 'LENGTH_BETWEEN_PERPS'
++       'FACTOR_1_A' 'FACTOR_2_A' 'FACTOR_1_B' 'BULB_PROTRUSION'


  INTEGER : 'NO_OF_SECOND_DECK' ' NO_OF_CRANES' 'NUMBER_OF_HOLDS'
++          'NO_OF_BULKHEADS' 'NO_REQUIRED_TEU' 'MAXIMUM_NO_TIERS_ON_DECK'
++          'NO_OF_REQUIRED_WATERLINES' 'NO_OF_INCLINATION_ANGLES'
++          'NO_OF_REQUIRED_DISPS' 'NO_OF_FREEBOARD_DECK'


  STRING : 'MACHINERY_LOCATION' 'HANDLING_GEAR_TYPE' 'DECK_PROFILE_FILE_NAME'
++         'LAYOUT_FILE_NAME' 'KNUCKLE_FILE_NAME' 'DESIGN_FILE_NAME'
++         'DB_TANK_DESCRIPTION' 'DB_TANK_CAPACITIES' 'SIDE_TANK_DESCRIPTION'
++         'SIDE_TANK_CAPACITIES'

  LOGICAL : 'DEFAULT_STABILITY_CRITERIA' 'STATIC_STABILITY' 'DYNAMIC_STABILITY'
++          'INTACT_STABILITY' 'BULBOUS_BOW_FITTED' 'CARGO_HANDLING_GEAR_FITTED'
++          'LENGTH_RESTRICTION_REQUIRED' 'BREADTH_RESTRICTION_REQUIRED'
++          'DEPTH_RESTRICTION_REQUIRED' 'DRAFT_RESTRICTION_REQUIRED'


  REAL LIST : 'SHEER_ORD_FWD'(10) 'SHEER_ORD_AFT'(10)
++            'LOC_SHEER_ORD_FWD'(10) 'LOC_SHEER_ORD_AFT'(10)
++            'HATCH_LENGTH'(10,5) 'HATCH_WIDTH'(10,5)
++            'LONGL_POS_OF_HATCH_CTR'(10,5) 'TRANS_POS_OF_HATCH_CTR'(10,5)


  INTEGER LIST : 'NUMBER_OF_HATCHES'(10) 'CONTAINER_ON_CL'(10,5)
```

Figure 3.5 Example of the type declaration section of an INCODES knowledge base.

```
!*****************************************************************************
!                    P A R A M E T E R   D E S C R I P T I O N S
!*****************************************************************************


!-----------------------------------------------------------------------------

  PARAMETER DESCRIPTION    :   LENGTH_BETWEEN_PERPS
! ---------------------------------------------

  The parameter LENGTH_BETWEEN_PERPS represents the length of the vessel
  between the fore and  aft perpendiculars.  The parameter has the units
  'metres'.

  DESCRIPTION END

!-----------------------------------------------------------------------------


   PARAMETER DESCRIPTION    :   DEPTH_TO_UPPER_DECK
! ---------------------------------------------

  The parameter DEPTH_TO_UPPER_DECK represents the depth of the vessel
  from the top of the keel to the underside of the upper deck at the side of
  the vessel. The parameter has the units 'metres'.

  DESCRIPTION END

!-----------------------------------------------------------------------------


   PARAMETER DESCRIPTION    :   NO_OF_SEA_DAYS
! ------------------------------------------

  The parameter NO_OF SEA_DAYS represents the number of days that the vessel
  is expected to spend at sea on a given voyage. Obviously it is dependent
  upon the length of the particular voyage and the average speed of the vessel.

  DESCRIPTION END

!-----------------------------------------------------------------------------
```

Figure 3.6 Example of knowledge base parameter descriptions.

3.1.3.3 Knowledge representation.

The basic production rule technique for knowledge representation used in the INCODES system has already been described, with an indication of the rule-based knowledge having been given. As mentioned previously, the rules are basically constructed from logical operators and qualifiers, together with other key words which enable the qualification and conclusion components of the rules to be represented. The knowledge representation language described here provides a fairly large natural language vocabulary so that qualifications and conclusions can be expressed in a near-natural language form. Typical examples of the near-natural language vocabulary used in rule definitions are given in Figure 3.7. In order to increase the flexibility of the knowledge representation language, the user is not restricted to a single set of instructions with which to encode the rules, but a number of alternatives are provided from which the knowledge base creator can choose those which he prefers to use. In addition to the vocabulary described above, the knowledge representation language provides the knowledge base creator with the ability to specify all of the mathematical functions provided by FORTRAN 77. The language enables the user to utilise these functions by using either their recognised FORTRAN 77 abreviations or symbols, or by specifying an alternative symbol which is contained in the index library of the knowledge representation language. This library can be extended by the system user in accordance with his personal preferences to provide a larger range of alternative symbols. Figure 3.8 shows a part of the symbol index library containing some of the alternative symbol representations. Examples of the use of mathematical functions in the knowledge representation language are given in Figure 3.9.

3.2 Structure of the KRL Compiler.

As previously mentioned, the task of the knowledge base compiler is to take the information contained in the knowledge base, written in terms of knowledge representation language statements, and translate it into valid FORTRAN 77 code. In simple terms, this translation involves the compiler searching the knowledge base for the recognised knowledge representation language statements and replacing them with their valid FORTRAN 77 equivalents.

The INCODES knowledge base compiler operates by breaking code into individual statements, checking that those statements are valid and generating the equivalent

```
DEFINE RULE   :  019-NUMBER_OF_BULKHEADS
----------------------------------------

GOAL : 'NO_OF_BULKHEADS'

NOTE  :  The following rule is taken from Lloyd's Rules.

  IF ('LENGTH_BETWEEN_PERPS' IS LESS THAN OR EQUAL TO 65.0) AND
  ('LENGTH_BETWEEN_PERPS' IS GREATER THAN 0.0) AND ('MACHINERY_LOCATION'
  IS "TWO_THIRDS_AFT") THEN 'NO_OF_BULKHEADS' IS EQUAL TO 4

  RULE END


DEFINE RULE   :  041-COLLISION_BULKHEAD
---------------------------------------

GOAL : 'POSITION_MAX'

NOTE  :  The following rule is taken from Lloyd's Rules.

  IF ('BULBOUS_BOW_FITTED' IS FALSE) AND ('LENGTH_BETWEEN_PERPS' IS
  GREATER THAN 200.0) THEN 'POSITION_MAX' IS EQUAL TO 0.08 TIMES
  'LENGTH_BETWEEN_PERPS' MINUS 'FACTOR_2'

  RULE END


DEFINE RULE   :   009-MASS_OF_CARGO_HANDLING_GEAR
-------------------------------------------------

GOAL : 'MASS_OF_SINGLE_CRANE'

  IF ('CARGO_HANDLING_GEAR_FITTED' IS TRUE) AND ('HANDLING_GEAR_TYPE' IS
  "SINGLE_PEDESTAL_CRANE") THEN 'MASS_OF_SINGLE_CRANE' IS EQUAL TO 75.0

  RULE END
```

Figure 3.7 Examples of typical knowledge base rules.

```
DEFINE FORMULA   :   009-LIGHTMASS
----------------------------------

GOAL : 'LIGHTMASS'

   'LIGHTMASS' IS EQUAL TO 'STEELMASS' PLUS 'MACHINERY_MASS' PLUS
   'OUTFIT_MASS'

FORMULA END


DEFINE FORMULA   :  011-DISPLACEMENT_LCG
----------------------------------------

GOAL : 'TOTAL_LCG'

  'TOTAL_LCG' IS EQUAL TO ('DEADWEIGHT_LCG' TIMES 'DEADWEIGHT' PLUS
  'LIGHTMASS_LCG' TIMES 'LIGHTMASS') DIVIDED BY 'DISPLACEMENT'

FORMULA END


DEFINE FORMULA   :  014-REQUIRED_FUEL_CAPACITY
----------------------------------------------

GOAL : 'REQUIRED_FUEL_CAPACITY'

  'REQUIRED_FUEL_CAPACITY' IS EQUAL TO 'NO_OF_SEA_DAYS' TIMES
  24 TIMES 'DELIVERED_POWER' TIMES 'SPECIFIC_FUEL_CONSUMPTION'

FORMULA END
```

Figure 3.9 Examples of typical knowledge base formulae.

K.R.L. Symbol	FORTRAN Equivalent
IS EQUAL TO	=
IS	=
=	=
*	*
+	+
/	/
-	-
POWER	**
SINE	SIN
SIN	SIN
COSINE	COS
COS	COS
TANGENT	TAN
TAN	TAN
ARCTANGENT	ATAN
ARCTAN	ATAN
ATAN	ATAN
ARCSINE	ASIN
ARCSIN	ASIN
ASIN	ASIN
ARCCOSINE	ACOS
ARCCOS	ACOS
ACOS	ACOS
INTEGER	INT
INT	INT
REAL	REAL
FLOAT	FLOAT
ABSOLUTE	ABS
ABS	ABS
LOGARITHM	ALOG10
LOG10	ALOG10
LOG	ALOG10
FALSE	.FALSE.
TRUE	.TRUE.
SQRT	SQRT
SQR	SQR

Figure 3.8 The INCODES KRL symbols.

statements in FORTRAN 77, as shown in Figure 3.10.

The process of breaking up statements within the knowledge base is called lexical analysis. The lexical analysis part of the compiler does not need to know what each statement means, but simply when it has ended. In the context of the INCODES knowledge representation language, the language segments can be summarised as follows:

- Parameters or symbols: a character, followed by an underscore or more alphanumeric characters.

- Integers: a digit, followed by blanks or more digits.

- Floating points: a digit followed by a blank or a decimal point and more digits.

- Special symbols: either single characters, e.g. +, *, or composite symbols, e.g. IF, SINE, POWER etc.

The INCODES lexical analyser is able to recognise the statements contained in a knowledge base by scanning each line of text for the occurrence of the above language segments. The individual segments for which the analyser searches is determined by the contents of index files, an example of which is shown in Figure 3.11. By consulting these files the lexical analyser becomes aware of the valid language tokens and also their FORTRAN 77 equivalents. The adoption of this approach means that the valid language segments are not hard-wired into the compiler thus enabling the syntax of the knowledge representation language to be customised by the user to suit individual tastes and preferences.

The parameters which the lexical analyser accepts as being valid are obtained from the parameter declaration section of the knowledge base. This requires that all parameters to be used in the knowledge base are declared in the parameters declaration section prior to being used in the main body of the knowledge base.

The validity of the statements contained in a particular knowledge base is determined by the parser. The parser checks that the language segments occur in the sequence required so that they can be translated into valid FORTRAN 77 statements. The rules

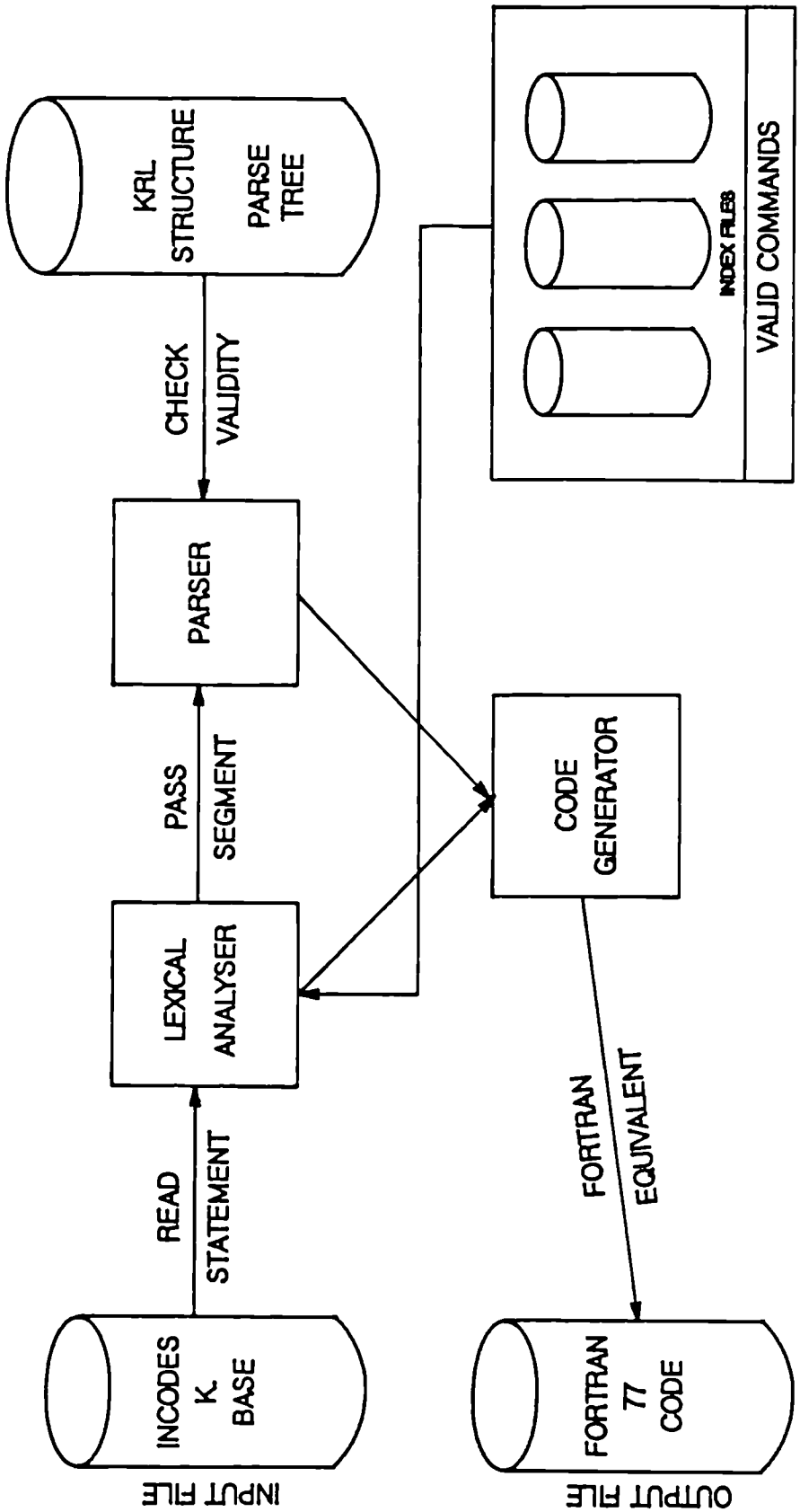

Figure 3.10 Structure of the INCODES KRL compiler.

KNOWLEDGE REPRESENTATION LANGUAGE SYNTAX

K.R.L. Statement	FORTRAN Equivalent
IS GREATER THAN OR EQUAL TO	.GE.
IS LESS THAN OR EQUAL TO	.LE.
IS THE EQUIVALENT OF	.EQ.
IS NOT THE SAME AS	.NE.
IS EQUIVALENT TO	.EQ.
IS GREATER THAN	.GT.
IS NOT EQUAL TO	.NE.
IS THE SAME AS	.EQ.
IS LESS THAN	.LT.
IS EQUAL TO	.EQ.
IS UNTRUE	.NOT.
IS FALSE	.NOT.
IS TRUE	----
AND	.AND.
OR	.OR.
IS	.EQ.
>=	.GE.
>	.GT.
<=	.LE.
<	.LT.
=/	.NE.
=	.EQ.

Figure 3.11 The INCODES KRL statements.

by which the validity of the statements is judged are held in an information structure known as a parse tree, an example of which is shown in Figure 3.12. Once the statements contained in the knowledge base have been accepted as being syntatically and structurally correct, they can be translated into valid FORTRAN 77 statements ready for translation into machine code by the ANSI FORTRAN 77 compiler, thus enabling them to be accessed by the inference engine of the expert system shell.

3.2 The inference engine.

As discussed in Chapter 2, the inference engine is the means by which the information contained in the knowledge base is interrogated, and the associated rules invoked and relevant facts created.

As mentioned in Chapter 2, the inference engine of an expert system performs four main tasks:

- matching
- selecting
- firing
- actioning.

It is responsible for invoking the rules held in the knowledge base and updating the working memory with the newly generated facts. It decides on the best path to be taken through the knowledge base in its attempt to arrive at a solution.

3.2.1 Determination of parameter relationships.

A typical INCODES knowledge base will contain a considerable amount of knowledge in the form of production rules, external procedures, default values, empiricisms, etc. As the information contained in the knowledge base is not required to be in any specific order, that is the rules do not have to appear in the knowledge base in the order that they are to be invoked, one of the main tasks of the inference engine is to decide on the possible sequence or sequences of firing of the rules. In order to do this, the inference engine must first examine the complete knowledge base and identify each symbol or parameter and how and where it is assigned, ie. by rule, by empirical formula, by user definition, by default declaration or by external procedure. This involves checking each rule, formula, etc., to determine where each of the declared

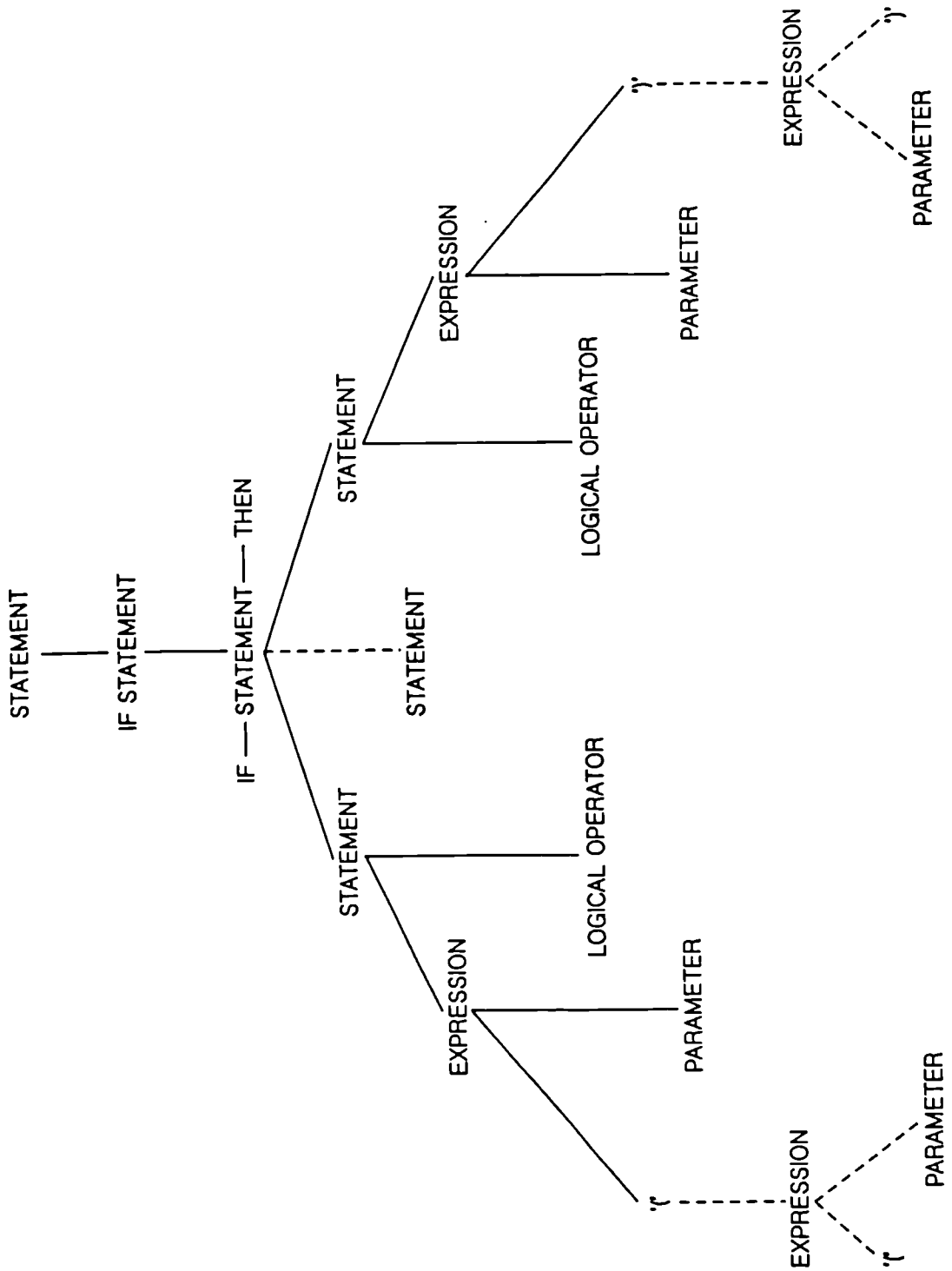

Figure 3.12 Example of a parse tree for the IF....THEN statement.

parameters is the goal or subject of the statement. It must however be appreciated that a single parameter could be the goal of a number of rules or formulae which involve different qualifications or conditions.

Once the goals or subjects of the rules, formulae etc., have been determined, the inference engine then has to identify the parameters which are involved in the qualification part of the rules or right hand side of the formulae, etc. This allows the inference engine to determine the relationships between the parameters and the nature of the dependencies between them. For example, from the following rule the inference engine could deduce that the parameter *position min* is directly dependent upon three other symbols, *length between perps*, *bulbous bow fitted*, and *factor 1*:

IF (*bulbous bow fitted* is false) AND
(*length between perps* is less than or equal to 200.0)
THEN (*position min* = 0.05 * *length between perps - factor 1*)

From the above it is obvious that the symbol *position min* can only be determined once the values of the three symbols on which it is dependent become known. The relationship between these four symbols can be expressed diagrammatically as shown in Figure 3.13.

The above rule makes use of the logical operator AND, but could quite easily have included the OR operator. The use of the OR operator complicates the dependency relationships of the parameters involved, in that the goal of the rule can be achieved without all of the other associated parameters being known. For example:

IF (*intact stability satisfied* is false) OR
(*dynamic stability satisfied* is false)
THEN (*stability satisfied* is false)

The above rule suggests that *stability satisfied* can be assigned a value if either *intact stability satisfied* or *dynamic stability satisfied* becomes known, and that it is not dependent on both of these symbols being determined. This form of dependency is shown diagrammatically in Figure 3.14.

An obvious extension to the examples given above is the case involving combined use of the AND and OR logical operators:

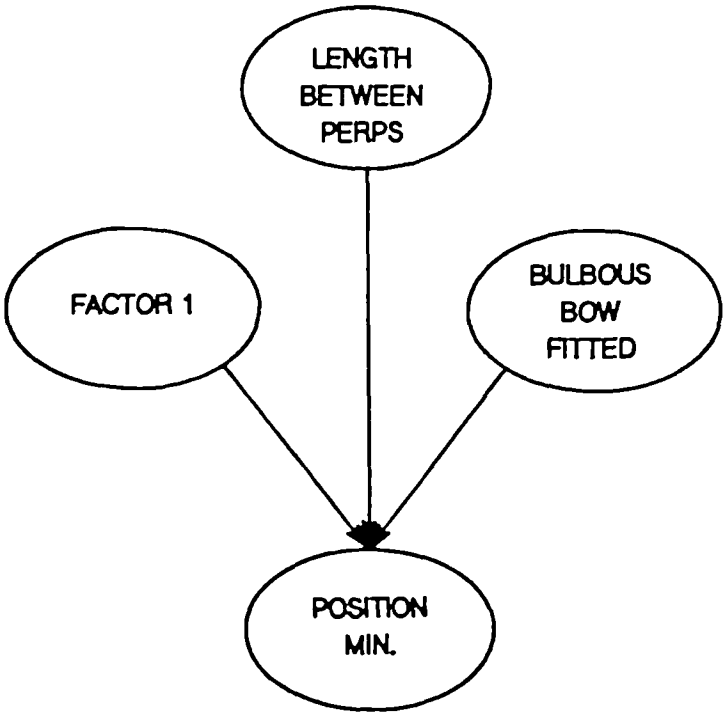

Figure 3.13 Example of parameter relationships.

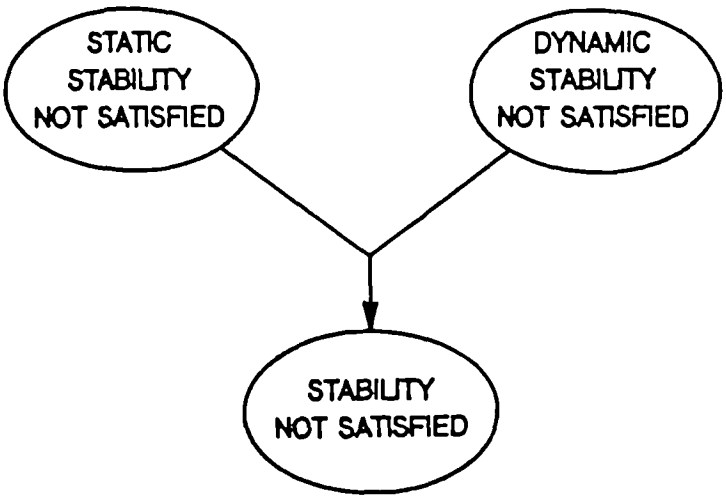

Figure 3.14 Example of parameter relationships.

IF ((*bulbous bow fitted* is true) AND
(*length between perps* is less than or equal to 200.0)) OR
(*factor 1* is greater than 10.0)
THEN (*position max* = 0.08 * *factor 2*)

The above rule suggests that the symbols upon which *position max* is dependent can be placed into two distinct groups. The first group contains the symbols *bulbous bow fitted* and *length between perps*, and the second comprises the symbol *factor 1*. It should be noted that the symbol *factor 2* is a member of each of the two groups as *position max* is unconditionally dependent upon it. This grouping of the dependencies is shown diagrammatically in Figure 3.15. Obviously the symbol *position max* becomes known when all of the members of either of the two groups are known and is not dependent on all of the involved symbols being determined.

In a similar manner to the way in which relationships and dependencies between symbols are derived from rules, knowledge base formulae also enable relationships to be determined as indicated below:

required fuel capacity = (*no of sea days*+*no of days reserve*) * 24
* *delivered power* * *specific fuel consumption*

From the above formula it can be derived that *required fuel capacity* is dependent on *no of sea days*, *no of days reserve*, *delivered power* and *specific fuel consumption*. This relationship can be expressed diagrammatically as shown in Figure 3.16.

3.2.2 Matching and invocation.

Once the inference mechanism has determined the relationships and dependencies of the parameters contained in the knowledge base, this enables the matching process to be carried out. That is, the knowledge base can be scanned and new facts deduced and added to the working memory when dependencies are fulfilled in the manner described above. This matching process can only continue as long as new facts are being created, and so eventually the matching will stop when no new facts can be generated. At this point the inference mechanism can only continue by receiving additional information from the system user. In order that the inference engine asks the user for the most pertinent information, a selection process must be carried out by the inference engine. This process involves the engine examining the complete knowl-

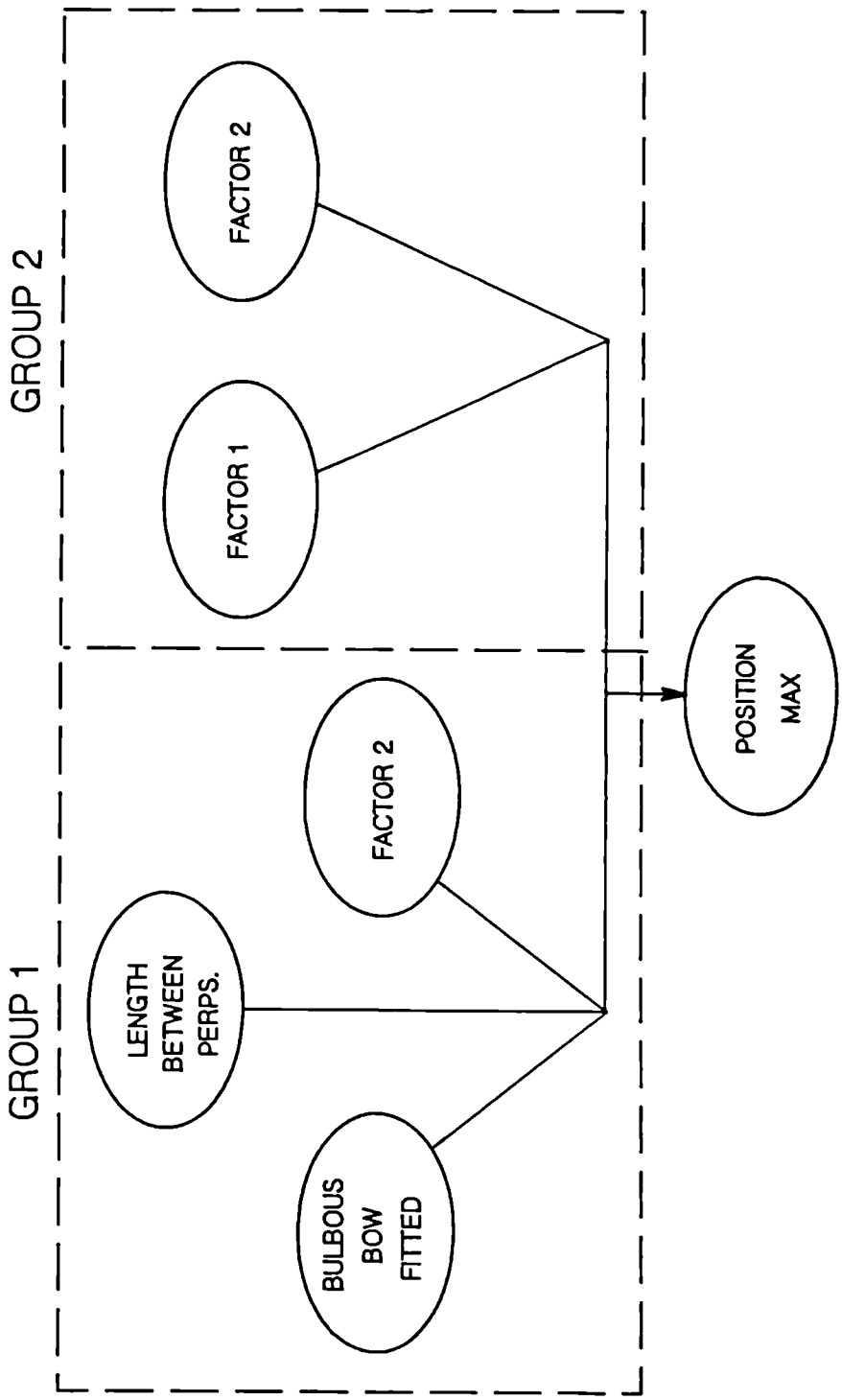

Figure 3.15 Example of parameter relationships.

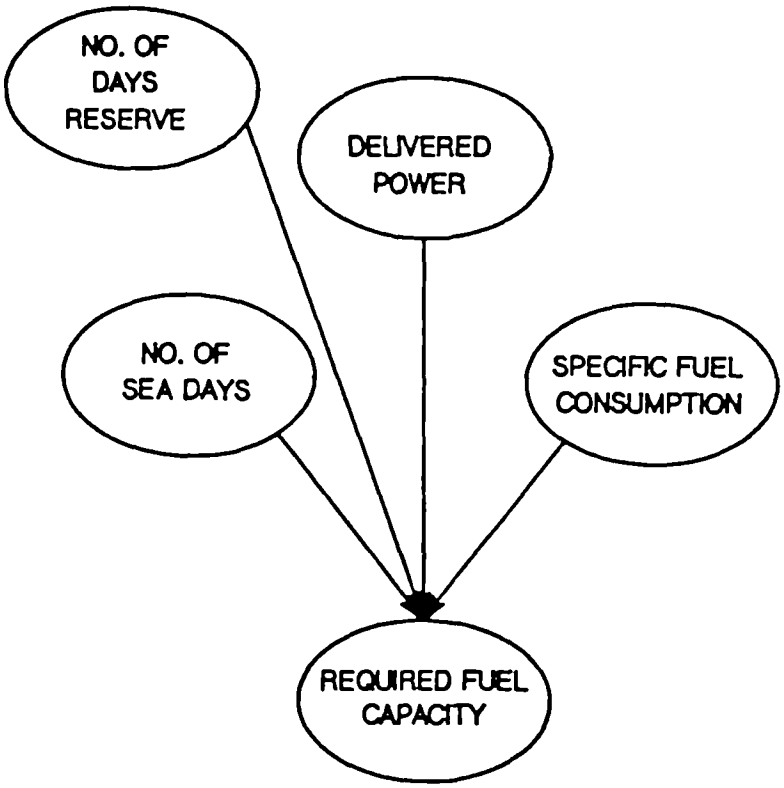

Figure 3.16 Example of parameter relationships.

edge base in terms of parameter relationships and dependencies. This requires an extension of the process described earlier, which simply looked at direct dependencies, to cover indirect relationships.

The concept of a parameter being dependent on one or more other symbols has already been discussed, but it must be appreciated that these symbols themselves will be dependent on other symbols. If all symbol dependencies are identified, a much more complex picture emerges. The complete picture of the parameter relationships for a particular knowledge base could look similar to Figure 3.17. The inference engine has to build up this complex picture so that it can progress through the decision space and invoke rules and determine facts. When the inference engine has decided that all the requirements for a particular symbol to be determined have been satisfied, then it uses its knowledge of where the symbol is assigned, ie. the exact rule, formula, external routine, to execute the statement and produce the value for the symbol. This fact can then be added to the working memory.

3.2.2.1 Invocation of user input statements

As mentioned earlier there will come a point in a consultation where a user input item is required in order that the investigation can continue. In such cases the inference engine must decide which is the user input which would have the most beneficial effect on the proceedings. To do this, the engine adopts a search strategy based on the assumption that any line of backward reasoning (back-tracking through the decision space) will eventually lead to a user input. An example of such a search is shown in Figure 3.18, where the inferencing has stopped due to the inability of the inference engine to generate any new facts. A number of alternatives are open to the inference engine at this stage as a number of user inputs have not yet been specified. The inference engine proceeds by looking at all of the unknown symbols associated with the current goal, as indicated in Figure 3.19. Once these have been identified, the engine analyses the dependencies of these symbols to determine how many unknowns are directly involved with each one. As, at this stage in the proceedings, each unknown represents a potential user input, it would appear reasonable to assume that the symbol which is reliant upon the least number of unknowns should receive prime consideration. From Figure 3.19 it can be seen that symbol **Y** would appear to involve the least number of unknowns and should therefore be considered first. As a second step, the dependencies of each of the unknowns associated with **Y** are considered in turn

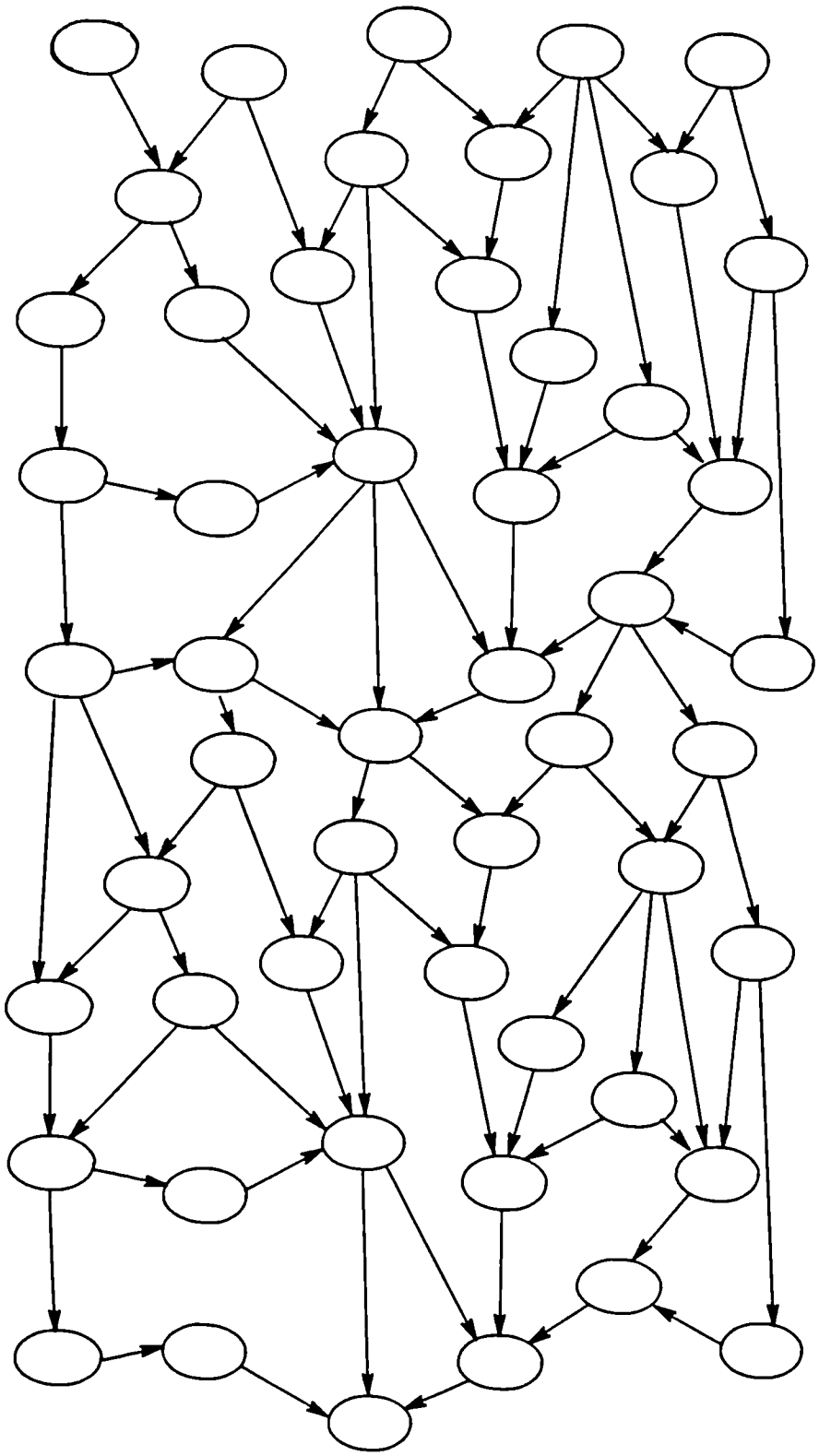

Figure 3.17 Example of a hypothetical search space.

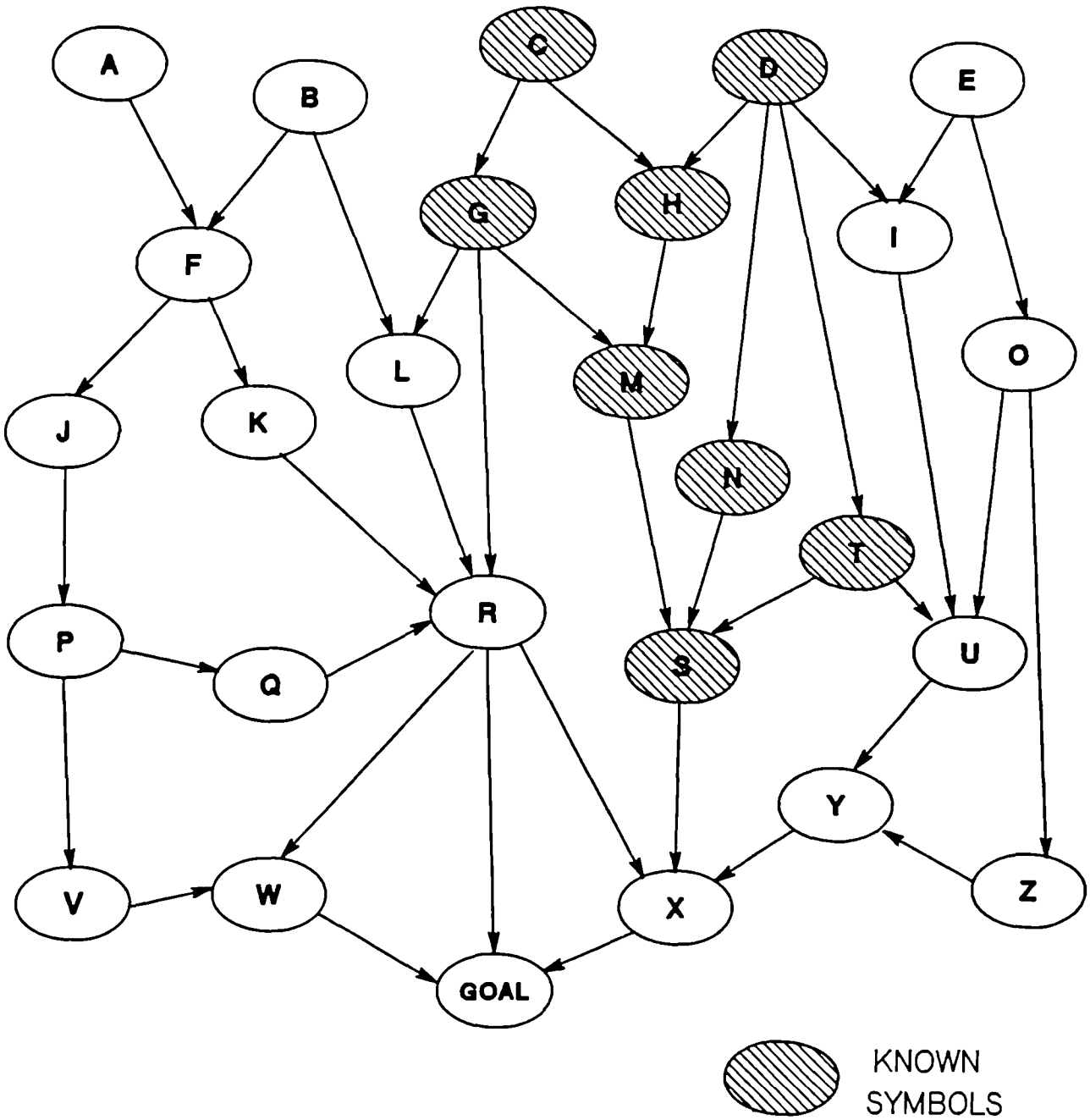

Figure 3.18 Example of a search halted due to insufficient information.

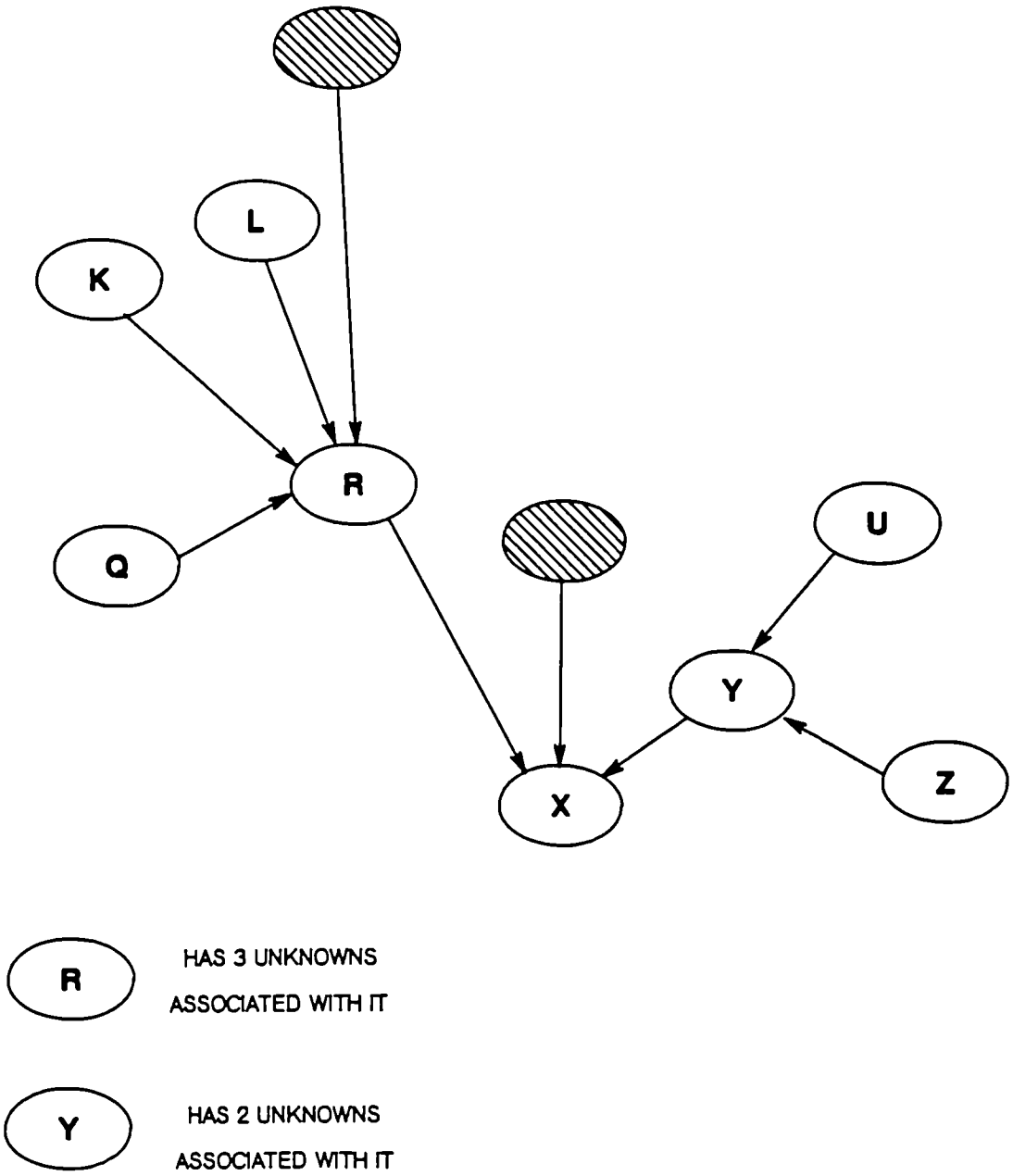

Figure 3.19 An examination of the cause of the stopped search.

to determine which of these symbols has the least number of unknowns associated with it. The selection of the symbol at this level, with the least number of unknown dependencies enables the whole process to be repeated. Remembering the original assumption that any line of backward reasoning will eventually lead to a symbol that is specified by user input, this process will result in the determination of the user input which will have the most beneficial effect on the progress of the investigation. This user input may enable new facts to be generated immediately, but more likely than not, another of the unknowns upon which symbol **Y** is dependent will have to be considered in a similar way to that described above. The above process is described diagrammatically in Figure 3.20.

As the above process causes the search of the problem space to progress quite rapidly along a single line of reasoning, the technique adopted is said to be a *depth-first* approach. The use of such a technique means that a particular line of reasoning is followed until it is either exhausted or a conclusion has been reached. This technique is highly beneficial to the user as it means that a single line of reasoning is followed either to a conclusion or until it is exhausted, with the result that any questions which the user is asked will all follow a particular pattern and the line of reasoning behind the questioning will be quite apparent. This is in contrast to an alternative search technique, the *breadth-first* approach, where the line of reasoning is not always made obvious as the inference engine moves around the decision space in a rather dis-jointed manner.

By using the methods outlined above, the inference engine of the INCODES shell is able to determine which rules, etc. are to be invoked and which questions are to be asked of the user. It also ensures that the working memory is constantly updated as new facts become known during the progress of the consultation session.

In addition to providing the basis for determining the sequence in which rules are to be invoked and user input requested, the analysis of the dependency relationships of the knowledge base parameters allows the inference engine to record the exact sequence of symbol determination and therefore to back-track and display lines of reasoning if requested to do so by the system user. The INCODES inference engine therefore provides the means to fulfil one of the basic requirements of any expert system, that is the ability to justify conclusions reached or to explain the lines of reasoning which have been followed. These features of the inference engine will be

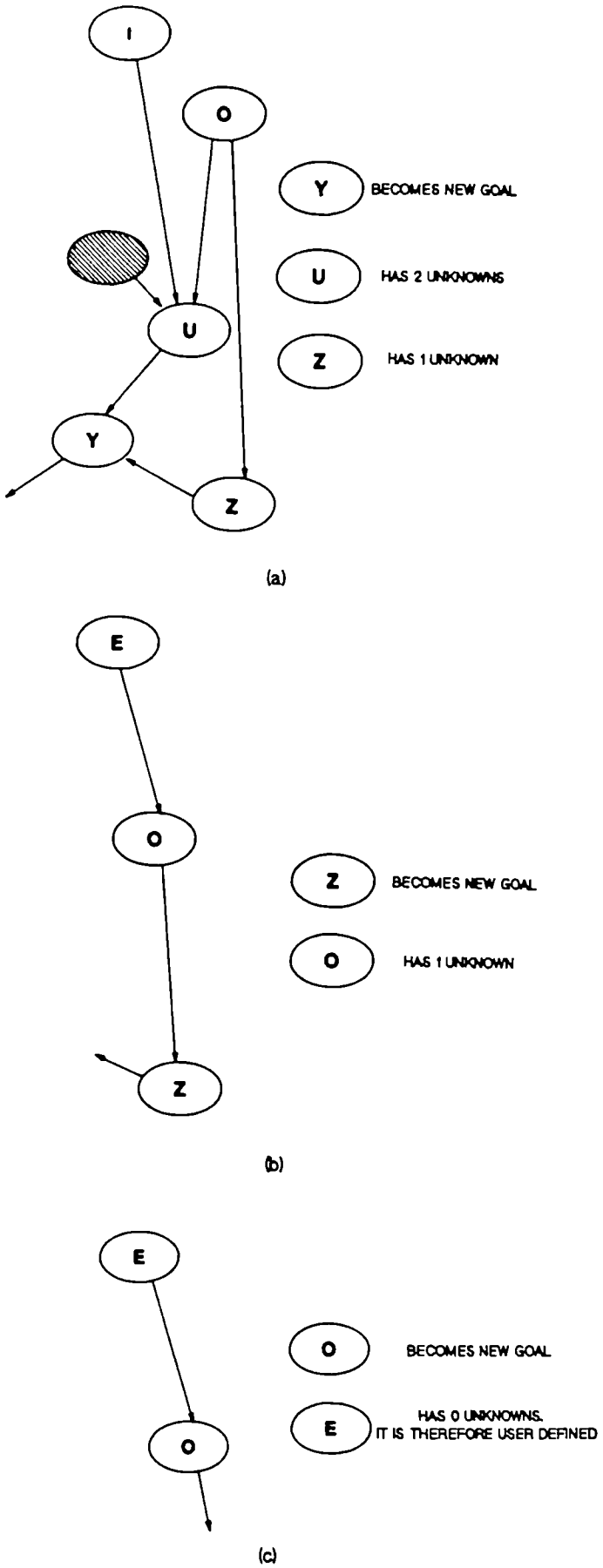

Figure 3.20 Back-tracking through the decision space.

further discussed when the user interface of the shell is considered.

The basic dependency relationship approach is also utilised at the start of any consultation session in order to determine which question should be asked of the system user first. This arises from the fact that the inference mechanism does not place any emphasis on the order in which user input items appear in the knowledge base, unlike many other expert systems. It simply assumes that the knowledge base was not created in a structured way and that the statements contained in it have been assembled in a completely random manner.

In order to determine which of the user input items should be prompted for first, the inference engine uses the previously described dependency relationship information to assess which user input item would have the most beneficial effect, that is the user supplied piece of information which has the most direct and indirect dependencies. Once this has been determined, the particular question is asked of the user and the rule invocation process proceeds in the normal manner.

As mentioned previously, one important feature of an expert system is its ability to proceed with incomplete information, in contrast to procedural-type programs which require a full set of input data in order to function correctly. This feature of expert systems, to be able to side-step parts of the search space which are dependent on unknown information, is derived from the fact that the inference mechanism has a complete picture of the search space. An indication from the user that a required input is unavailable will cause the inference engine to attempt to select another line of reasoning which will eventually lead to the desired goal. Unfortunately there will invariably be occasions when no alternative line of reasoning is available and so the inference engine will persistently ask for the specified item of input. In such cases it will obviously be the responsibility of the system user to either endeavour to obtain the required input item or to decide to terminate the consultation session.

3.3 The user interface.

Although the inference engine is the controlling mechanism for the expert system and is therefore central to the whole operation of the system, the difference between an expert system which is considered to be good and one which is not, is often to be found in the user interface. This interface provides the means by which information gener-

ated by the inference engine is communicated to the system user and it also provides the user with the ability to issue instructions to the inference engine in order to influence its progress through the decision space. In general, a user interface should be based on natural or near-natural language instructions which the user can use in order to communicate with the system. The system in turn should be able to understand these natural language instructions by carrying out simple parsing on the user input character strings. This feature of an expert system which allows communication in natural language or near-natural language statements has the effect of building the confidence of the system user and encouraging him to exploit the considerable abilities of the system. Without the benefits of such a user-friendly interface there is no doubt that any system would be under-utilised and its full potential would not be exploited.

With the above points in mind a fairly comprehensive user interface was developed for inclusion in the INCODES shell.

The INCODES user interface comprises a set of user specifiable commands which enable the user to initiate a range of responses from the expert system which contribute toward the user gaining a greater understanding of the scope and structure of the knowledge contained in the associated knowledge base, and the steps being taken by the expert system during the progress of the current consultation.

In order to increase the flexibility of the user interface, the commands available to the system user do not possess a strict structure or syntax, but most of them have a number of alternative forms. Providing alternative ways to initiate a given process within the system again encourages the system user to exploit the full capabilities of the system.

The ability of the INCODES interface to recognise alternative forms of user commands arises from the procedures incorporated in the system for pattern recognition, string reduction and string concatenation. These procedures have the ability to accept user-supplied instruction strings, examine them to determine their intended meanings and then finally initiate the required response. The particular techniques used for string handling permit the user to issue commands in a non-case sensitive manner, that is the commands can contain any combination of upper and lower case characters.

One of the main features of the INCODES shell user interface is that the user can issue interrogative commands at any point during the consultation session, even when the inference engine is prompting for a user-supplied data item. This enables the user to maintain complete awareness of the state of the consultation, assure himself of the value of any parameter, or to question assumptions or lines of reasoning. The acceptance of one of the acceptable user commands by the system, simply results in the temporary suspension of the consultation until the desired action has been carried out and the user completely satisfied. Only then will the inferencing and rule invocation carry on in the usual manner.

A summary of the basic commands which can be issued to the system via the user interface is given in Figure 3.21, together with a brief explanation of the purpose of each one. As previously mentioned, the set of commands which will initiate actions by the expert system can be extended or modified by the system user to suit individual tastes and preferences.

A full explanation of the meaning and syntax of each of the commands is available to the user at run-time by means of an on-line documentation facility. This feature can be invoked simply by typing a question mark which results in all of the acceptable commands being listed, with detailed information on a particular command being obtained by typing a question mark followed by the relevant command.

Some of the user specifiable commands are simply a means of interrogating the knowledge base to determine where particular parameters are defined, etc., but others actually initiate actions involving the inference mechanism, such as those which examine lines of reasoning and require back-tracking through the decision logic. These particular commands make use of the inference mechanisms awareness of the structure of the decision space as a whole and the lines of reasoning, which have been followed during the course of the consultation. This back-tracking process results in the working memory being modified to reflect the changed position within the decision space. Back-tracking to a previously encountered location in the decision space requires that the working memory is modified, with some parameters being set to the state of unknown, to give the impression that the current point in the decision space is being visited for the very first time in the current consultation. On this basis, continuous back-tracking would result in the consultation arriving back at the original starting point with all of the knowledge base parameters being set to the state of unknown.

```
??              display this message.
HELP [option]   display more information about the specified option.
BASES           display the currently available Knowledge Base.
LOAD            load the specified knowledge base into the shell.
GO              start the consultation.
STOP            stop the current consultation.
RETRIEVE        retrieve a previous consulation session.
STORE           store the current values of all parameters.
CHANGE          change the value of an individual parameter.
STATUS          display the status of the current session.
WHERE           where is an individual parameter assigned.
VALUE           display the value of a particular parameter.
BACK            go back to previous question.
DATAFILES       what datafiles are available for display.
DISPLAY         display the contents of a particular datafile.
PRINT           print the contents of a particular datafile.
ASSIGN          volunteer the value of a particular variable.
WHAT            what parameters have been assigned.
WHY             why is a particular question being asked.
DESCRIBE        describe a particular parameter.
ADVICE          give advice on the question being asked.
CONTENTS        display content information of a particular K.Base.
HOW             explain the reasoning behind the achievement of a goal.
SPAWN           invoke an external program/command shell.
SYSTEM          issue an operating system command.
```

Figure 3.21 The available INCODES user commands.

The ability of expert systems to back-track through the decision logic is one which contributes to differentiating them from normal computer systems.

Another feature of the INCODES user interface is its ability to communicate with the base operating system of the host computer. Allowing the user to interrogate file systems and carrying out general house-keeping duties, without leaving the INCODES environment, is an obvious advantage and considerably improves the flexibility of the system. Communication with the base operating system of the host computer also permits the invocation of programs which are not directly related to the particular INCODES knowledge base in use. This invocation of external programs is not restricted to application programs but can also include text editors, compilers, communications programs etc., thus allowing a wide range of activities to be undertaken whilst remaining within the general confines of the INCODES system environment.

The user interface specified and developed for the INCODES shell is considered by the author to be quite comprehensive in terms of the facilities which it provides. The ability of the system user to customise the instruction set of interface commands is considered to be a unique feature of the INCODES system, and is one which can only have the effect of encouraging better utilisation of the system as a whole.

3.4 The explanatory/advisory interface.

This feature of an expert system shell is closely connected with the user interface, as previously described, in that they both share the same basic function. They are both intended as vehicles for system/user communication, with the explanatory/advisory interface being more concerned with the communication of information from the system to the user, unlike the user interface which is primarily concerned with permitting the user to communicate his requirements to the system.

The prime purpose of the INCODES explanatory/advisory interface is to enable the information stored in the knowledge base to be presented to the system user in the most convenient form possible. The most basic method available as a means of informing the user, is the simple display of textural material on the computer monitor. Another, and by far the most effective method of information transfer, is by graphical representation. A single diagram can communicate a vast amount of information, equivalent to many pages of text, in a matter of seconds. The incorporation of

graphical information in the explanatory capability of the INCODES shell was therefore considered essential.

The explanatory/advisory interface of the INCODES shell provides two main services to the user, as indicated below:

- It provides additional information to assist the user in responding to system prompts.

- It informs user as to the significance of the goals achieved.

The first service provided by the explanatory/advisory interface is available to assist the system user when he has been requested to supply information to the system. The ability of the interface to provide additional information concerning the parameter under consideration can often help the user to gain a better understanding of the need for the particular information being requested. This additional information can take the form of a piece of explanatory text or a graphical representation of the parameter. The ability of the expert system shell to provide user assistance in this way, goes some way towards providing an application with a degree of self documentation.

The second service provided by the interface, that of informing the user as to the significance of goals achieved, allows the progress of a consultation to be monitored. This is achieved by the explanatory/advisory interface displaying the intermediate goals which have been reached, (ie. the values which the parameters have been assigned), and any relevant information which is contained in the knowledge base. The relevant knowledge base information is extracted by the explanatory interface when the parameters on which it is dependent have been evaluated. For example the following piece of advice would be displayed by the interface once the associated condition had been satisfied:

IF (*intact stability satisfied* is false)
THEN
DISPLAY ADVICE (Note: intact stability is not satisfied)
END ADVICE

This simple example illustrates the ability of the expert system to advise the user after

reasoning with the available information. This advisory function of the explanatory/ advisory interface is a major feature of expert system applications as it provides a means of suggesting avenues open to the user in the event of a certain aspect of the conclusion being unacceptable. For example, an extension of the previous example could include advice as to the possible steps to be taken to rectify the problem of unsatisfactory intact stability:

IF (*intact stability satisfied* is false)
THEN
DISPLAY ADVICE
(The following options are available:
1) Add waterballast
2) Modify loading condition
3) Modify ship dimensions)
END ADVICE

The two examples given above are fairly general in that they make the user aware of various problems and suggest possible ways of solving those problems, but without providing any specific guidance. Further examination of the current state of the consultation by the expert system could involve an advisory statement, such as the one given below, being displayed:

IF (*intact stability satisfied* is false) AND
(*double bottom tank 1* is *empty*)
THEN
DISPLAY ADVICE
(Adding ballast to No.1 D.B.tank could have a beneficial
effect on intact stability)
END ADVICE

The above statement illustrates how the knowledge base associated with a particular application can be structured so as to provide a true advisory service to the user and not simply be a means of analysing user defined design proposals.

4. Summary of the INCODES expert system shell.

As can be seen from the preceeding description of the elements of the INCODES shell, a comprehensive expert system development tool has been developed for the solution of engineering design problems. The shell provides a unique combination of graphical features, user-friendly interfaces, analysis capabilities and scientific/mathematical functionality in a package which has the accepted engineering programming language, FORTRAN 77, as its base. The author considers that the INCODES shell provides all of the features required to facilitate the development of practical expert system based solutions to complex engineering design problems, and is especially suited to the development of the conceptual ship design system being considered here.

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CHAPTER 4

The Containership Concept.

SUMMARY.

This Chapter looks at the containership concept from its early days as converted tankers to the present-day specialised container-carrying vessel. The main features of containerships are described and the problems associated with their design and operation are discussed. In particular, the complex problems associated with the economic and safe operation of container-carrying vessels are highlighted. The problems to be considered in the specification and development of the conceptual ship design system are made apparent.

1. Introduction.

As previously mentioned, a decision was made at the start of the research project being described here, to initially restrict consideration to the containership concept when specifying and developing the various components of the system module. Before considering the various aspects of the containership design system it was first necessary to examine the containership concept in some detail to identify the many and varied features of this type of vessel which would influence the specification of and development of the system.

Containerisation can be considered as a *total transportation concept* with the cargo being handled in a unitised form suitable for carriage by sea, road, rail and inland waterway vehicles, with the containership being the seaborne link in the chain. Container services often operate from a container base where small packages of break-bulk cargo are consolidated into full container loads ready for shipping, this being of considerable benefit to those involved in the transport of small packages. Containerisation also offers a true door-to-door service to those requiring the shipment of full

container loads due to the ease with which the container units can be transferred between the different modes of transport involved.

The origins of the concept of containerisation can be traced to the start of the twentieth century, with the introduction of container services in the United States, but it was not until after the Second World War that the use of containerisation became widespread. Many of the early vessels used for the carriage of container cargo were modified general dry cargo vessels and tankers [4.1] with the first true containerships being the fully converted C-2 type tankers introduced by Pan-Atlantic in 1960. Alongside the development of the seaborne containerisation concept, land based transportation systems were also considerably enhanced during this period to take full advantage of the gains to be made from this form of cargo. It was also around this time that attempts were made to standardise the physical and strength characteristics of the containers themselves by organisations such as the American Standards Association (ASA), and later by the International Organisation for Standardisation (ISO).

2. Advantages of containerisation.

The advantages of containerisation are considerable and varied, and have resulted in around 85% of present liner cargo being carried in a containerised form. These benefits can be summarised as follows [4.2] :

- Lighter and hence cheaper packaging of the individual items of cargo can be utilised as considerable protection is afforded to the cargo by the container units.

- The fact that containerisation is a capital rather than labour intensive mode of cargo transportation means that costs are less vulnerable to increases in labour rates, thus permitting services to be kept competitive.

- Reduced cargo handling times, combined with generally faster vessels, contribute to considerably shorter transit times.

- Larger and faster container vessels have allowed fleet sizes to be

rationalised with container carrying tonnage replacing the slower and smaller 'tween deck vessels on many deep sea routes.

- Container vessels have a higher utilisation rate than normal break-bulk types.

- Delicate as well as dirty and hazardous cargoes can be carried with relative ease and safety.

- The secure nature of containerised cargo results in much reduced levels of pilfering, loss and accidental damage.

- The general reduction in transportation costs permits relatively low value cargoes to be carried thus provides a stimulus to world trade.

- Reduced cargo handling times results in less demand for berth space at loading/discharge ports.

- The adoption of containers of standard size permits interchangeability between the various modes of transport involved in the movement of goods.

3. Disadvantages of containerisation.

The carriage of cargo in containers does bring with it a number of quite significant problems, the most important of which are indicated below:

- Containerisation has associated with it a high level of capital investment both in terms of the specialised cellular vessels and the requirement for at least three sets of containers per ship. This high capital cost is often sufficient to put containerisation beyond the reach of many shipowners. The cost of providing the necessary shore-based facilities, such as specialised cargo handling equipment, road and rail terminals and storage space, can also be prohibitive.

- Some types of cargo are not suited to carriage by container, although these are becoming fewer with the introduction of new types of container

which permit the carriage of a wide range of cargo types. Some cargoes, such as livestock, are simply incapable of being carried in containerised form.

- Exporters with only a limited amount of cargo are unable to fill containers and so are unable to take advantage of the rates offered. This problem can be overcome to some extent by the consolidation of container loads at container bases, although this process will incur extra costs due to the additional labour involved.

- Port areas will tend to be considerably increased due to the area required for container stacking and handling.

- Containerisation tends to exaggerate traffic imbalances in some cases.

- The task of ensuring that containers, spread around a number of port countries and ports, are fully utilised can present significant problems to the operator.

- Some countries have restrictions on the size and weight of units which can be transported by road, a fact which has prevented the use of some of the larger and heavier containers on some routes.

- The transportation costs associated with containerisation tend to be low while the terminal costs are relatively high, with the result that longer routes offer the possibility of higher profits while the shorter routes tend to be more suited to service by short-sea RO-RO vessels.

- Container operations will obviously include the movement of large numbers of empty units. This can be a very costly operation as the empty containers have to occupy slots which could be used for the carriage of revenue-earning loaded units. The loss of revenue can be minimised by carrying empty containers in the uppermost on-deck tiers therefore utilising those slots which could not be filled with loaded containers due to stability considerations.

- The high capacities of modern container vessels, operating on multiple port-call services, requires that computer-based loading arrangement systems [4.3] are utilised to ensure that port delays caused by additional cargo handling operations are minimised or avoided completely.

4. Development of the containership concept.

From its origin as tankers converted for the carriage of unitised cargoes, the containership has developed into a complex, highly specialised vessel, designed to maximise the benefits to be gained from high cargo handling rates and reduced port times. The development of the containership from its early form to the present day concept has been marked by a number of significant changes in design philosophy, mainly as a result of changes in the world economic climate, changes in trading patterns and major world political events.

Early container vessels were associated with low carrying capacities due to being closely related to ship types whose prime function was the carriage of bulk or break-bulk cargoes. The development of specialised container carrying vessels resulted in drastic increases in container capacity for a given volumetric capacity.

The first of these specialised container vessels were characterised by capacities around 1200 TEU (twenty foot equivalent units) with service speeds of around 22 knots. The first of the large European containerships, such as those developed by Overseas Containers Limited [4.4], with a capacity of 1300 TEU and a speed of 22 knots, were designed in the late 1960s for the Europe to Australia route via the Suez Canal. World events, culminating in the closure of the canal in 1967, forced these vessels to sail via the Cape of Good Hope with the result that they were being operated under sub-optimal conditions on a route for which they had not been designed. During the ensuing period, containerships increased in size and speed to take advantage of the economy of scale in a manner similar to the development of the oil tanker into the VLCC and ULCC classes of vessel. These large container carriers, with capacities of up to 3000 TEU, were powered by twin or triple screw steam or diesel plant with outputs in the region of 70,000 to 85,000 shaft horse power to give a service speed of around 26 knots.

After a number of years of successful operation, these vessels were badly hit by

steeply rising fuel costs and hence were forced to operate at reduced speeds in order to moderate fuel consumption and the associated costs. In later years many of these vessels were re-engined from their twin/triple screw configurations to single screw diesel plant, as illustrated by [4.5] and [4.6].

In this period of high fuel prices a new generation of containership designs emerged which possessed similar capacities to their predecessors but had much reduced powering requirements due to their lower design speeds. This reduction in speed resulted in fuller hullforms with the associated advantage of the vessels being able to carry the required complement of containers within much reduced main dimensions. The trend towards reduced speeds, increased propulsive efficiency, fuller hullforms and reduced main dimensions for a given capacity continued into the nineteen-eighties with the development of new classes of full cellular containerships and hybrid combination carriers suitable for the transportation of both containerised and RO-RO cargoes. The reduction in containership size and the improvement in propulsive efficiency of vessels of comparable capacity between 1973 and 1986 was illustrated by [4.7].

5. Aspects of containership design.

Modern container carrying vessels can usually be placed into one of the three main groups:

- pure container carriers
- combination container/RO-RO carriers
- general cargo vessels with a container carrying capability.

Within these main groups, further divisions can be made in terms of whether the vessel carries cargo-handling gear or not, the type of container securing equipment used, and so on.

Most modern general cargo vessels have a container carrying capability to some extent ([4.8], [4.9]), but their capacity tends to be restricted due to the relatively small hatch area/deck area ratio and the restricted deck stowage which results from stability considerations. The relatively low ballast capacity of such vessels can also impose severe restrictions on the possible loading arrangements which can be accommodated.

The combined container/RO-RO carrier, as typified by the Atlantic Container Line (ACL) G3 class of vessel [4.10], provides for the carriage of containerised cargo in both lift on - lift off and roll on - roll off modes, together with other roll on - roll off traffic. As can be seen from Figure 4.1, the cargo region of this type of vessel is divided into two distinct areas, the part intended for the carriage of RO-RO cargo and the cellular portion for the carriage of lift on - lift off container units. The positioning of the RO-RO section aft, means that access ramps can be located in the stern area and that the widest part of the vessel is utilised for the carriage of wheeled cargo with the result that lane lengths (a measure of RO-RO capacity) are maximised. In addition, the location of the cellular container spaces forward results in better utilisation of the more awkward spaces at the extreme forward end of the vessel, and improved trim and stability characteristics due to increased mass at the forward end. The safety of the vessel is also improved over the pure RO-RO carrier due to the incorporation of transverse sub-division into the cellular part of the vessel.

The specialised container carrying vessel is designed around the cargo unit to be carried with the dimensions, hullform and general layout being developed to maximise the capacity of the vessel. Various methods of securing the containers both below and above deck are used to ensure that the risk of cargo damage or loss is minimised and that the structural and operational integrity of the vessel is not compromised.

As can be appreciated from the above brief description of the three main types of vessel engaged in the transportation of containerised cargo, the concepts and problems associated with the design and development of such vessels are different in each case. In the context of the methodology being developed for the conceptual ship design system being described here, it was decided to concentrate on the pure containership whilst noting the enhancements required to the system to permit the other types of vessel to be considered at a future date.

5.1 The Cellular Containership.

The specialised containership, as previously mentioned, can either be considered as a deep sea vessel for the transportation of container units between major centres, or as a feeder vessel designed to provide a container distribution service from these major distribution ports. Both of these types of vessel will be designed so as to maximise

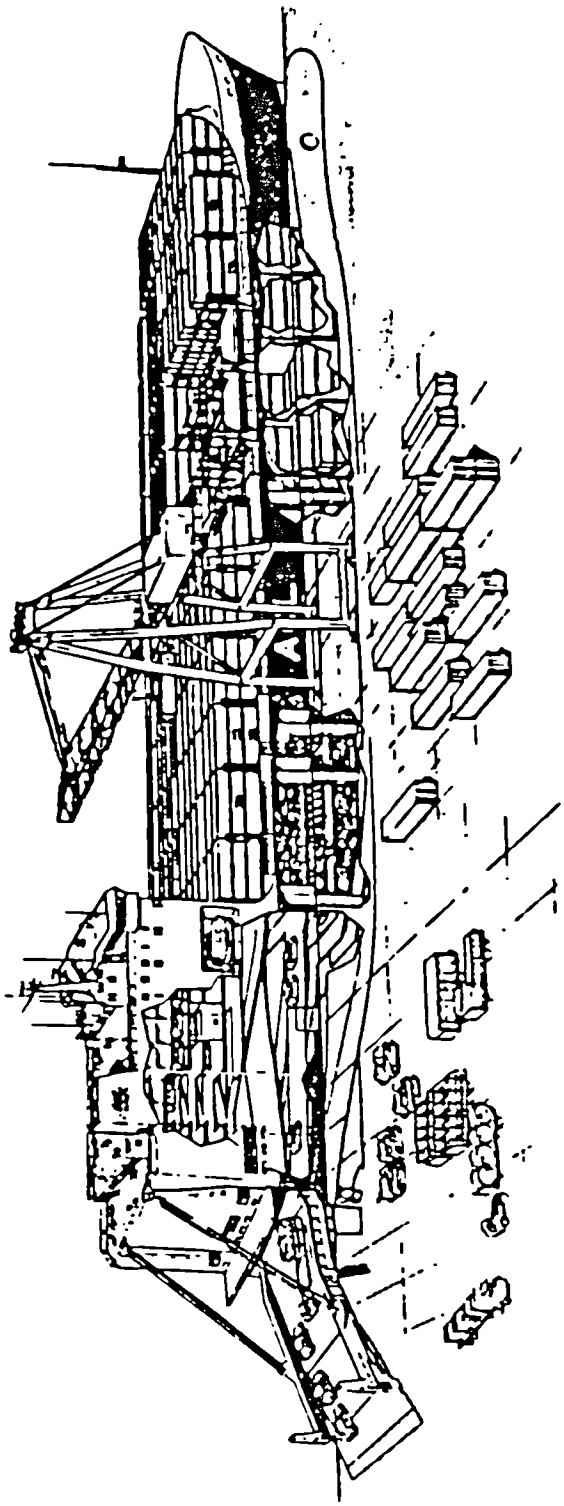


Figure 4.1 The ACL G-3 class of RO-RO containership.

their container carrying capability, with the major differences between them being in their respective capacities and the on-board facilities provided for cargo handling.

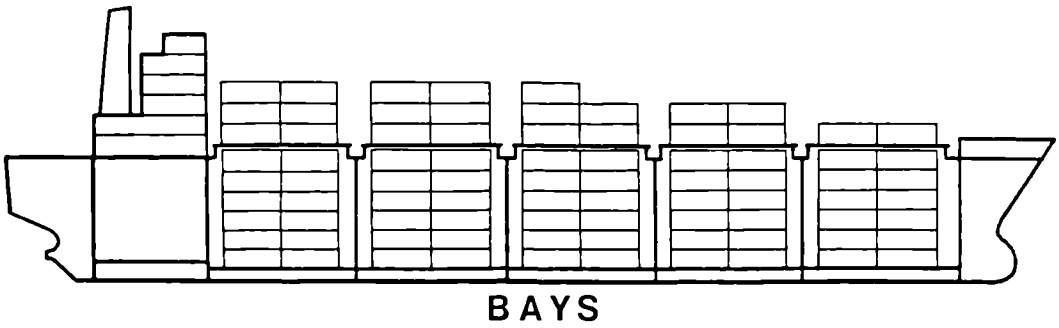
A modern deep-sea containership will typically have a capacity of 2500+ TEU with a service speed of around 18-24 knots, while the feeder type of vessel will have a much smaller capacity of up to 800 TEU, and a speed around 16-18 knots. Due to the fact that the larger container vessels operate on well defined liner routes between developed ports which possess land-based cargo handling equipment (such as gantry cranes and straddle carriers), there is little call for ship-board cargo handling facilities. As a result, the majority of these vessels will be of the gearless variety. On the other hand, many of the smaller container vessels will operate on a less well defined itinerary between ports which do not possess adequate shore-based cargo handling facilities, and as such will often be designed with ship-board container-handling gear such as fixed pedestal or travelling gantry cranes.

5.1.1 Main dimensions.

The main dimensions of containerships are obviously closely linked to the cargo to be carried, with the length, breadth and depth being functions of the physical size of the containers to be accommodated. For a specified container capacity, the dimensions of the vessel will be determined by the number of container bays, rows and tiers (as defined in Figure 4.2) which have to be accommodated, which in turn will be dependent on the shape and fullness of the associated hullform and the anticipated proportion of the total capacity to be carried on deck. An additional consideration arises from the intended operating routes and ports of call for the vessel, with the associated restrictions placed on vessel length, breadth, depth and draft by navigational features, such as the Panama Canal, and by those posed by berths and turning basins in ports.

5.1.1.1 Length.

The length of a containership can be considered as being made up of the sum of the length of the cargo spaces, the length of the machinery space and the forward and after peaks of the vessel. The length of the cargo spaces will obviously be a function of the number of container bays, the length of the containers involved and the required clearances to accommodate the container securing devices. In addition, consideration will have to be given to the incorporation of the necessary allowances



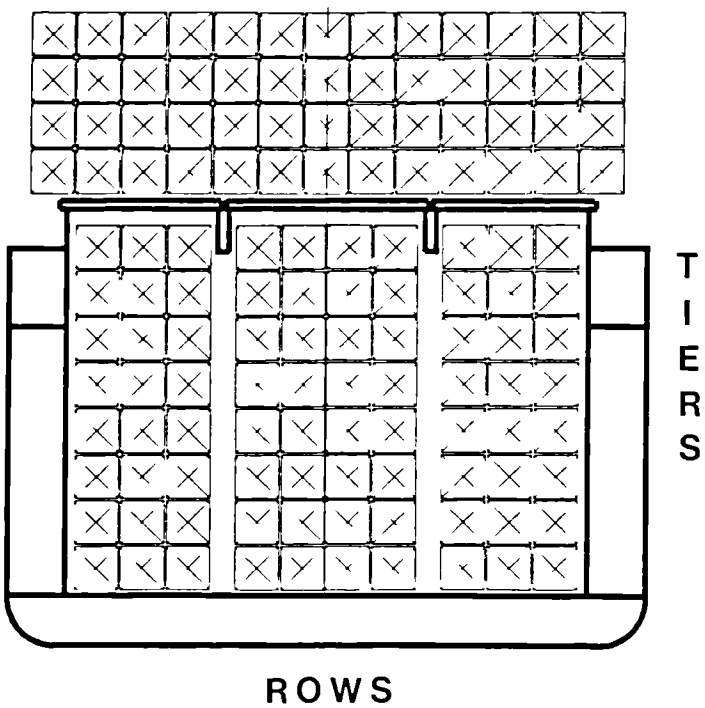


Figure 4.2 Definition of container bays, rows and tiers.

for structural members such as transverse bulkheads and web frames, and for any between hatch items such as cargo handling equipment (pedestal cranes) and deck houses. The type of container to be carried will also have an effect on the length of the vessel as, for example, port hole type refrigerated containers will obviously require the provision of considerable allowances for the cooling ducts at the end of the holds.

5.1.1.2 Breadth.

In common with the other main dimensions of the containership, the breadth of the vessel is basically a function of the size of the container unit. The overall breadth of the vessel will also be dependent upon the number of hatches which have to be accommodated across the beam of the ship as this will determine the number of inter-hatch deck girders which are required. The gaps required between the containers will depend upon the type of stowage equipment being utilised, for example, the type of cell guide system fitted in the vessel. Outboard of the hatches there is also the requirement for sufficient width of deck to provide the vessel with adequate longitudinal and torsional strength. The breadth of the vessel is obviously of prime importance to the stability characteristics, which is perhaps of greater concern in the design and operation of containerships than any other vessel type, and is an aspect of the containership concept which will be discussed in some detail later. Traditionally, the maximum breadth of a containership has been restricted by the maximum which could negotiate the Panama Canal. This limitation has also resulted in most shore-based cargo handling equipment being designed to work on vessels with the maximum Panama breadth. The first class of vessel to depart from the Panamax beam was the C-10 class of American President Lines [4.11] with their non-Panamax 39.4 metre beam. The benefits arising from this departure from the normal 32.2 metre maximum breadth are mainly to be found in improved stability characteristics which permit the vessels to be operated with much reduced amounts of water ballast than comparable capacity vessels restricted to the Panamax breadth. Improved stability also allows these vessels to operate with containers stacked five high on deck with the result that overall capacity is increased above that which would have been expected from the associated main dimensions.

5.1.1.3 Depth.

The depth of a containership is primarily a function of the size of the container unit,

with account being taken of the vertical gaps between the adjacent containers and the height of the tank top in the holds. The number of tiers of containers to be carried in the hold will be dependent upon the proportion of the total capacity of the vessel to be carried under the deck. It is normal for modern container vessels to carry 50% to 60% of their capacity in the holds with the balance being carried above deck. Some containership concepts have been proposed whereby the proportion of under-deck stowage ranges from 0% to 100%, as shown in Figure 4.3. The carriage of a larger proportion of the container cargo under deck does have the advantage of reducing the number of deck tiers thus avoiding the need for extensive lashing of the deck containers, but causes a number of problems concerning the design and operation of the vessel. For example, an increase in the number of tiers of below deck containers will result in increased stack loads requiring the double bottom structure to be specially strengthened to withstand the increased loading. Problems also occur as a result of the ability of the containers to resist crushing as caused by racking of the container end frames, although the chances of containers collapsing under the increased stack loads are reduced by the use of cell guide structures in the holds. A feature of high under-deck capacity vessels, which affects the operational efficiency, is the increased cargo-handling time required for the movement of under-deck containers as opposed to that required for those carried on-deck. This increase in cargo-handling time arises as a result of the hoist and slew operation associated with the loading/removal of under deck containers, compared to the simple slewing manoeuvre required when handling on-deck units, as illustrated in Figure 4.4., together with increased spotting time associated with on-deck containers.

5.1.1.4 Draft.

Containerships are associated with large freeboards and light loaded drafts. This light draft is due to the relatively low density of the cargo carried by containerships which results in displacements which are quite low in relation to the physical size of the vessels. Containerships are naturally deep vessels in order to accommodate the under-deck stowage, a feature which, when combined with the associated shallow drafts, results in the large freeboard typical of this type of vessel. The large freeboard associated with containerships has the effect of virtually eliminating the shipping of water onto the upper deck with the associated possibility of sustaining damage to the on-deck containers. The need for hatch covers to be watertight is also largely removed due to the reduced chance of water being shipped. As with the other main

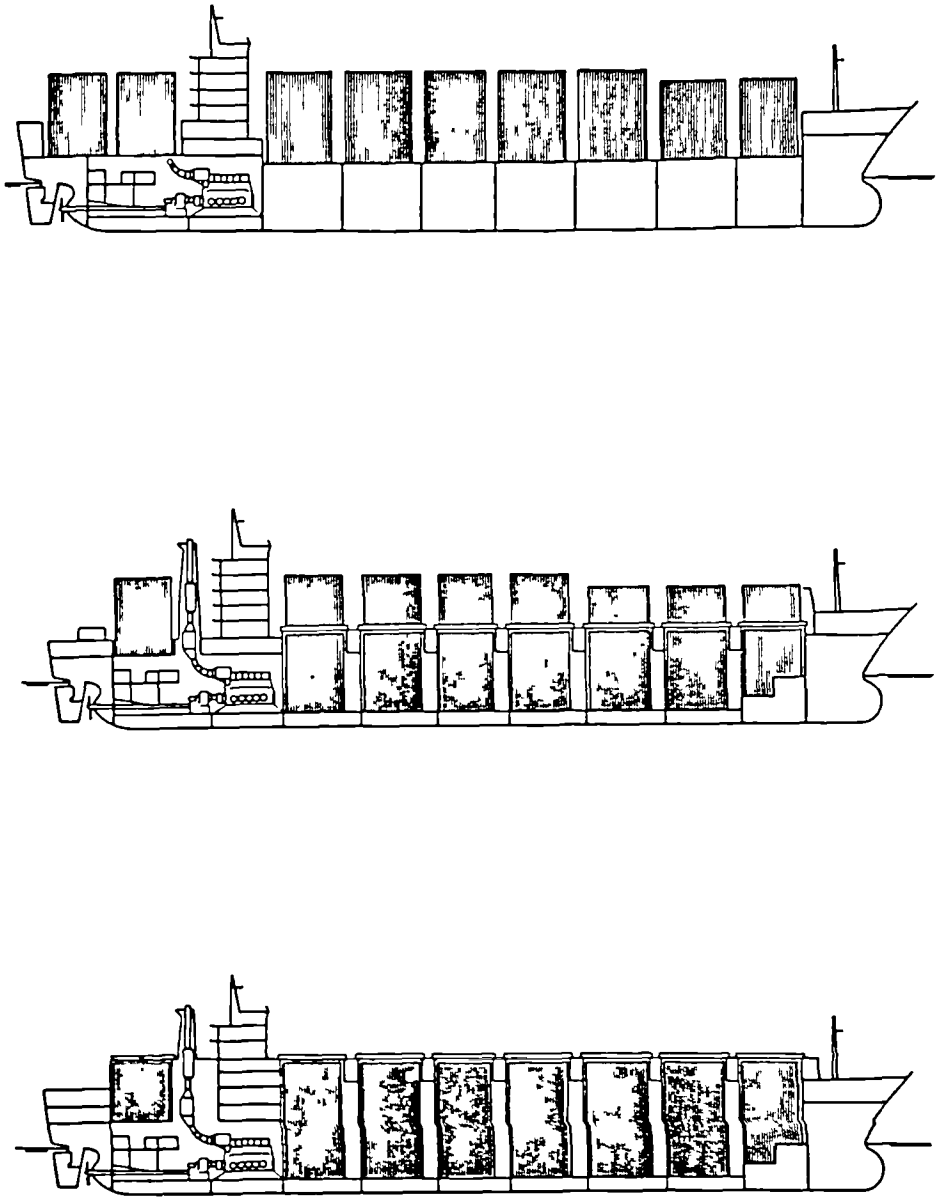


Figure 4.3 Proposals for the variation in the proportion of on-deck containers.

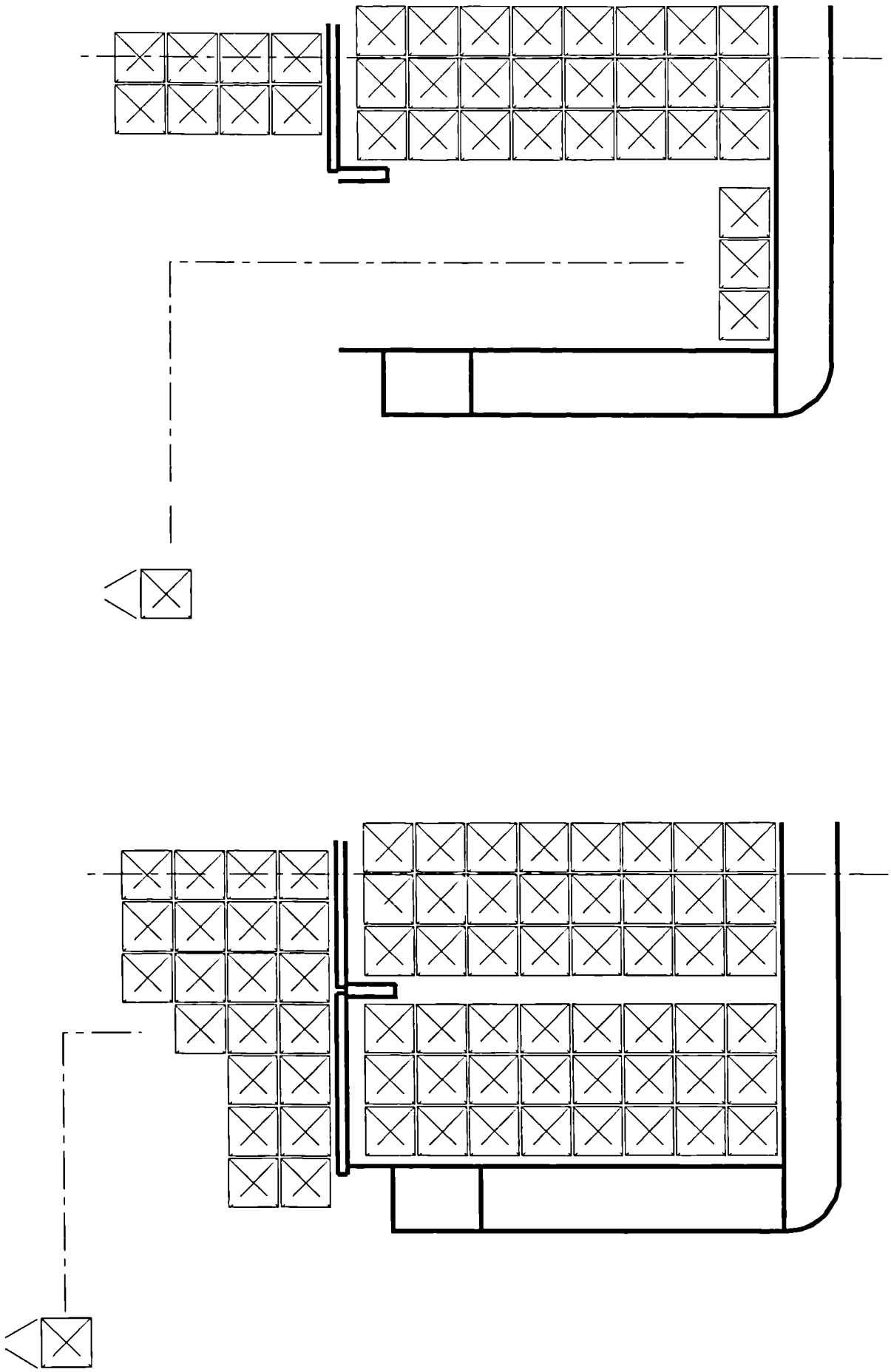


Figure 4.4 A comparison of the handling of deck and hold containers.

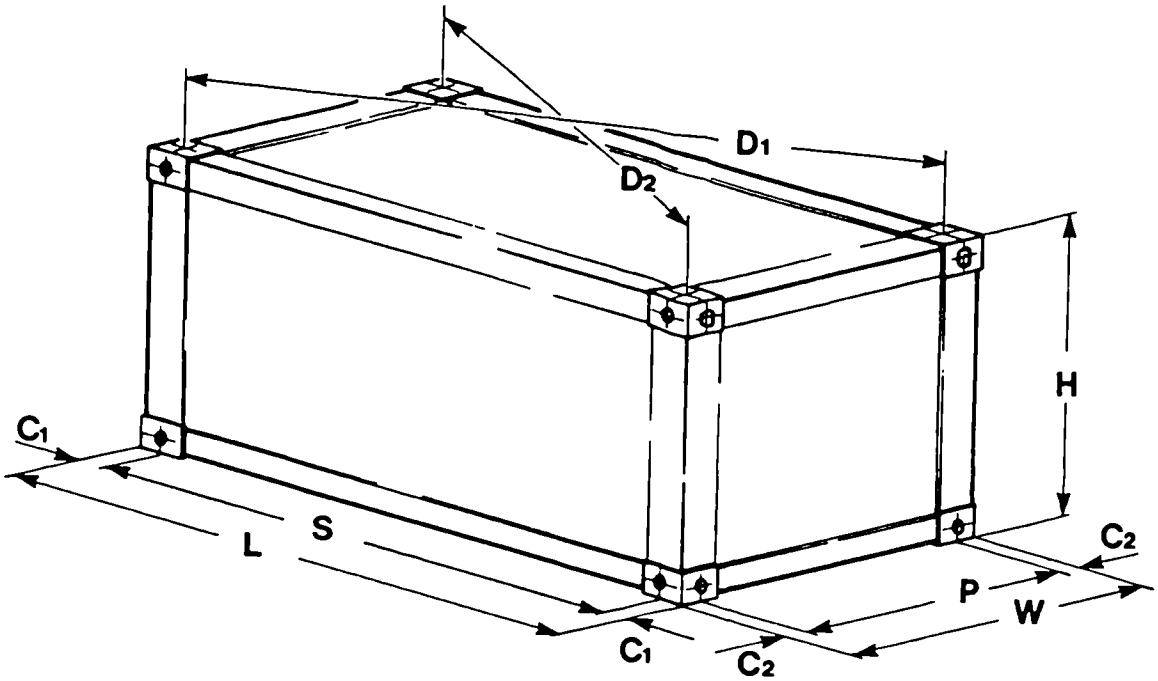
dimensions of the containership, the draft of the vessel will be subject to any restrictions associated with the ports in which the vessel is operated, and any navigational features which have to be negotiated.

5.1.2 Containers.

The basic dry container unit is a relatively thin skinned box built around a load bearing framework consisting of four vertical corner members connected by a header and a sill at each end. These end frames are tied together by longitudinal rails at the top and bottom of the container. The corner posts provide the main strength of the structure by transmitting the vertical loads generated by stacking containers in tiers. The container floor is supported by transverse members which transmit the loads imposed on the floor into the lower side rails. The sides and top of the container will usually be of relatively thin material stiffened either transversely or longitudinally. The roof will have sufficient strength to allow two men to walk on it without causing excessive deflections. A door at one end of the container will provide the means of access to the unit, with the other end being sealed. Corner fittings are provided at the top and bottom of each of the corner posts for lifting and securing purposes.

The range of container types available for the carriage of cargo has continued to expand as the demand for units to accommodate cargoes with particular requirements has persisted. There are presently very few cargoes which cannot be carried in a containerised form as units exist which fulfill even the most stringent requirements in terms of humidity and temperature control, and high levels of protection. As mentioned previously, attempts have been made to standardise the dimensions containers, although non-standard units continue to be used by some operators. The strength properties of the units were also standardised in order that problems associated with container crushing and deformation could be largely avoided. The sizes of the ISO standard containers are shown in Table 4.1, together with their maximum permitted loadings.

Many containerships are designed with a degree of flexibility in terms of the sizes of containers which can be carried, but this is usually limited to the ability to swap between standard 20 or 40 foot units as this virtually involves the simple positioning of two 20 foot containers in a 40 foot cell. Problems do occur, however, when attempting to design a vessel to accommodate more than one of the less common



FREIGHT CONTAINER DESIGNATION		LENGTH (mm)		WIDTH (mm)		DIFFERENCE D_1-D_2 D_2-D_1	C_1 mm	C_2 mm	HEIGHT		MAX. GROSS MASS
ISO 668	FEET	L	S	W	P				FEET	H (mm)	
1A	40'	12192^{+0}_{-10}	11985^{+4}_{-6}	2438^{+0}_{-5}	2259^{+0}_{-5}	19mm	101.5	89	8'	2438^{+0}_{-5}	30480 kg
1AA									8'6"	2591^{+0}_{-5}	
1AX									<8'	<2438	
1B	30'	9125^{+0}_{-10}	8918^{+4}_{-6}			16mm			8'	2438^{+0}_{-5}	25400 kg
1BB									8'6"	2591^{+0}_{-5}	
1BX									<8'	<2438	
1C	20'	6058^{+0}_{-6}	5853^{+3}_{-5}			13mm			8'	2438^{+0}_{-5}	24000 kg
1CC									8'6"	2591^{+0}_{-5}	
1CX									<8'	<2438	

OTHER CONTAINER HEIGHTS (NOT INCLUDED IN ISO/DIN) 9' AND 9'6"

Table 4.1 Particulars of ISO containers.

container sizes, such as 35, 45 or 48 foot units.

In addition to the normal dry containers, suitable for the carriage of most general cargoes, there are also refrigerated containers for the carriage of chilled and frozen goods, tank containers for the transportation of liquid cargoes, and open topped containers to accommodate awkward or bulky loads. Some of the various types of container unit available are shown diagrammatically in Figure 4.5.

The type or mix of types of container which a vessel is intended to carry will have a significant effect on its overall design. These effects will primarily be concerned with the physical size of the units and the effect on the main dimensions of the vessel, but will also result from the different loadings associated with the various types. For example, a fully loaded 40 foot container will occupy the same volume as two fully loaded 20 foot units but the stowage rate of the 40 foot unit will be much higher than the 20 foot containers (1.63 m^3/t in comparison to 2.20 m^3/t), a fact which has obvious implications for those aspects of the design concerned with trim and stability and longitudinal strength.

The ability of a vessel to carry containers suitable for the transportation of chilled or frozen cargoes will also require special consideration at the design stage. The overall effect on the design of the vessel will depend on whether the refrigeration unit is integral to the container itself or whether the cooling plant is provided by the ship with the containers being cooled by ducted air. Containers with integral refrigeration units will only require the provision of electrical power sockets in the container cell into which the cooling plant can be plugged, with there being little or no effect on the overall arrangement of the vessel. On the other hand, those containers which require an external source of cooling media will have a significant effect on the design of the vessel as the length of cargo spaces intended for the carriage of this type of container will be increased by the need to provide ducts for the supply and exhaust of cooling air to each of the containers.

5.1.3 Container stowage and securing.

Every aspect of the containership design process is influenced by the cargo unit itself. Apart from the main dimensions of the vessel being direct functions of the dimensions of the container unit, the sizes and arrangement of the cargo hatches will be

governed by the need to accommodate the cargo units. In addition, the structural arrangement of the vessel will be influenced by the requirement to absorb the static and dynamic loads imposed by the containers, and to provide adequate support and restraint in order to prevent their damage or loss.

5.1.3.1 Hold stowage.

The stowage and securing of containers in the holds of a vessel is normally achieved by means of a system of cell guides which not only greatly speeds up the loading and unloading processes, but considerably reduce the chances of container damage due to shifting or the development of eccentric forces on the container ends. A typical cell guide system consists of groups of four vertical guides (one ar each corner of the container) constructed from steel angle bars into which the containers are lowered, as shown in Figure 4.6, running the full depth of the vessel from hatch coaming level down to the tank top. The dimensions of the individual cells are selected so as to provide sufficient clearance over the nominal container sizes to avoid jamming when positioning the containers in the guides. The tolerances incorporated into the guides must also be sufficiently small such that shifting of the containers is minimised, and that the container spreader can be easily engaged when removing the containers.

The provision of a cell guide system in the holds means that the fastening together of the individual containers is unnecessary as all of the static and dynamic forces generated by the containers are transmitted directly into the ships structure by the cell guide members.

At the top of each cell guide there is obviously the need for some means of leading-in the containers, in both the longitudinal and transverse directions, to permit them to be quickly loaded into the guides without the need for the exact spotting of the units. The obvious method of providing this lead-in facility is to incorporate flare into the top of each of the guides as shown in Figure 4.7. As can be seen from the illustration, this arrangement results in the requirement for relatively large gaps between adjacent containers with the associated increases in overall ship dimensions. An alternative to this arrangement is one whereby the lead-in is achieved by means of a flip-flop system ([4.1], [4.4]) as shown in Figure 4.8. The use of this system results in the gaps between the containers being kept to a minimum, therefore ensuring that the best possible use is made of the available volume for the stowage of the containers.

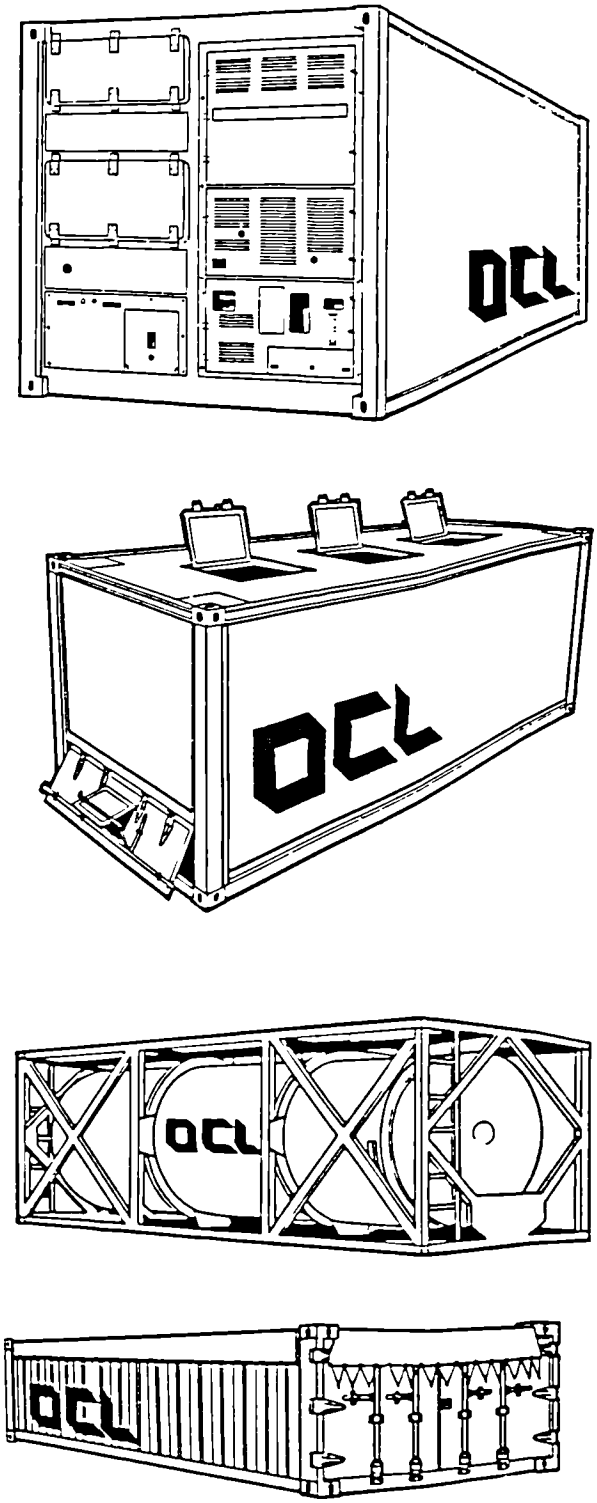


Figure 4.5 Examples of some of the various types of container unit.

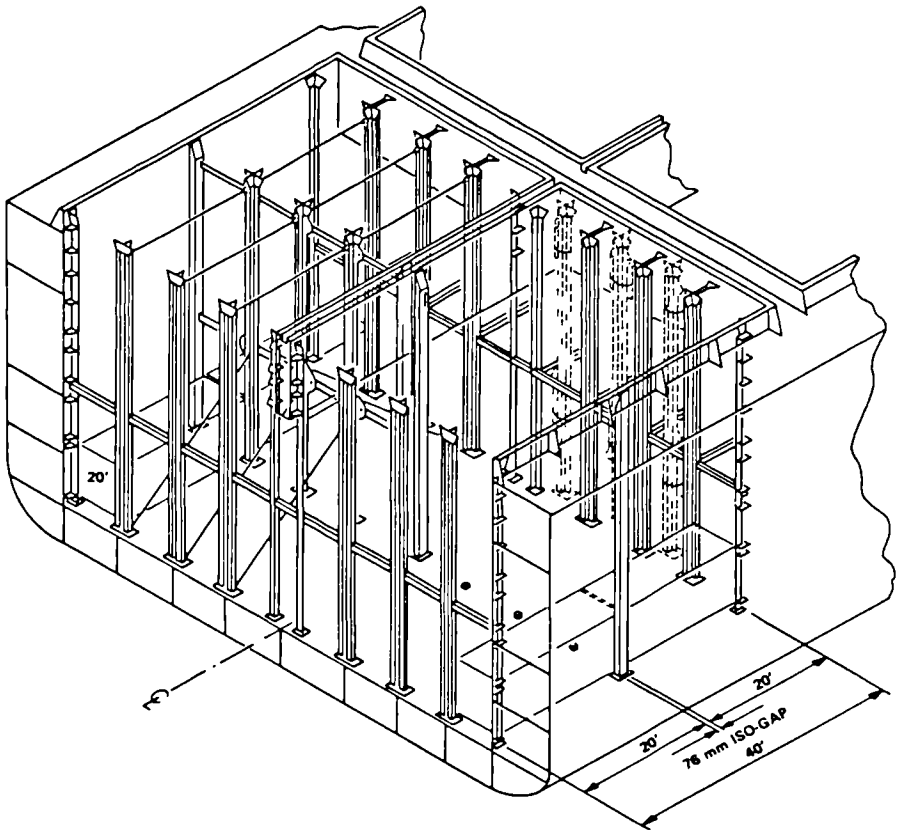
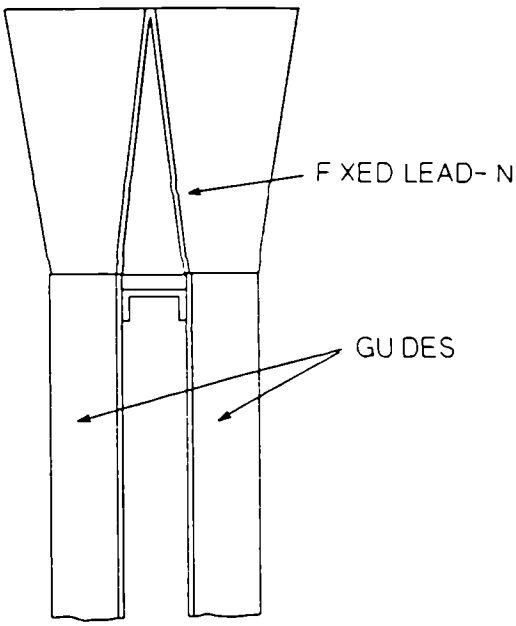


Figure 4.6 A typical hold cell-guide system.



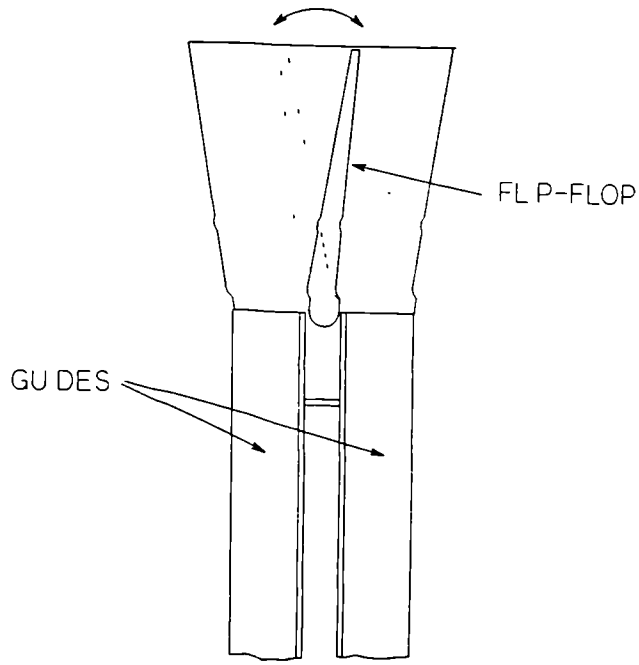


Figure 4.7 The fixed system of cell-guide lead-in. *Figure 4.8 The flip-flop system of cell-guide lead-in.*

5.1.3.2 Deck stowage.

The importance of the contribution of the on-deck stowage to the overall capacity of the container vessel has already been discussed. However the stowage and securement of containers above the deck does present some significant problems to both the ship designer and ship operator alike.

The containers carried on the deck of a vessel will be subject to significant forces due not only to the static stacking loads, but also to the motions of the vessel which result in significant accelerations and dynamic forces. The shipping of green seas can also subject the outboard containers to forces of a fairly high magnitude, but fortunately the large freeboard together with the usual fore-body flare associated with this type of vessel tends to reduce the chances of this problem occuring. The forces to which the containers, and hence the securing equipment are subject tend to limit the number of tiers which can be carried on deck. It being usual for a maximum of three to four tiers of containers to be carried on deck, with the carriage of five tiers being possible in some cases [4.11]. The magnitude of the forces to which a container is subject is largely dependent upon the mass it contains and the position which it occupies in the overall cargo block. These forces are usually determined by summation of the various components of force as induced by statics, ship motions, wind loading etc., as shown in Figure 4.9. Detailed procedures used to calculate the magnitude of these forces are fully described in [4.12] and [4.13].

There are many alternative ways in which the on-deck containers can be secured to the vessel with the traditional ones using a system of twistlocks and lashing rods and wires, as shown in Figure 4.10, to absorb the forces acting on the containers. Examples of such arrangements are given in Figure 4.11. However, the fastening and unfastening of the lashing wires and twist locks is a very time consuming process and can lead to considerable delays and increased port time. With modern container vessels where a significant proportion of the total capacity is carried on-deck, this can result in a substantial decrease in the effectiveness of the whole transportation operation. As a result of the problems associated with the lashing of deck containers, several alternative methods for container securing have been developed and implemented, with varying degrees of success. Some of the approaches are concerned with reducing the proportion of the capacity carried on deck, as previously discussed, to the point where all of the containers are carried in the holds of the vessel. Although

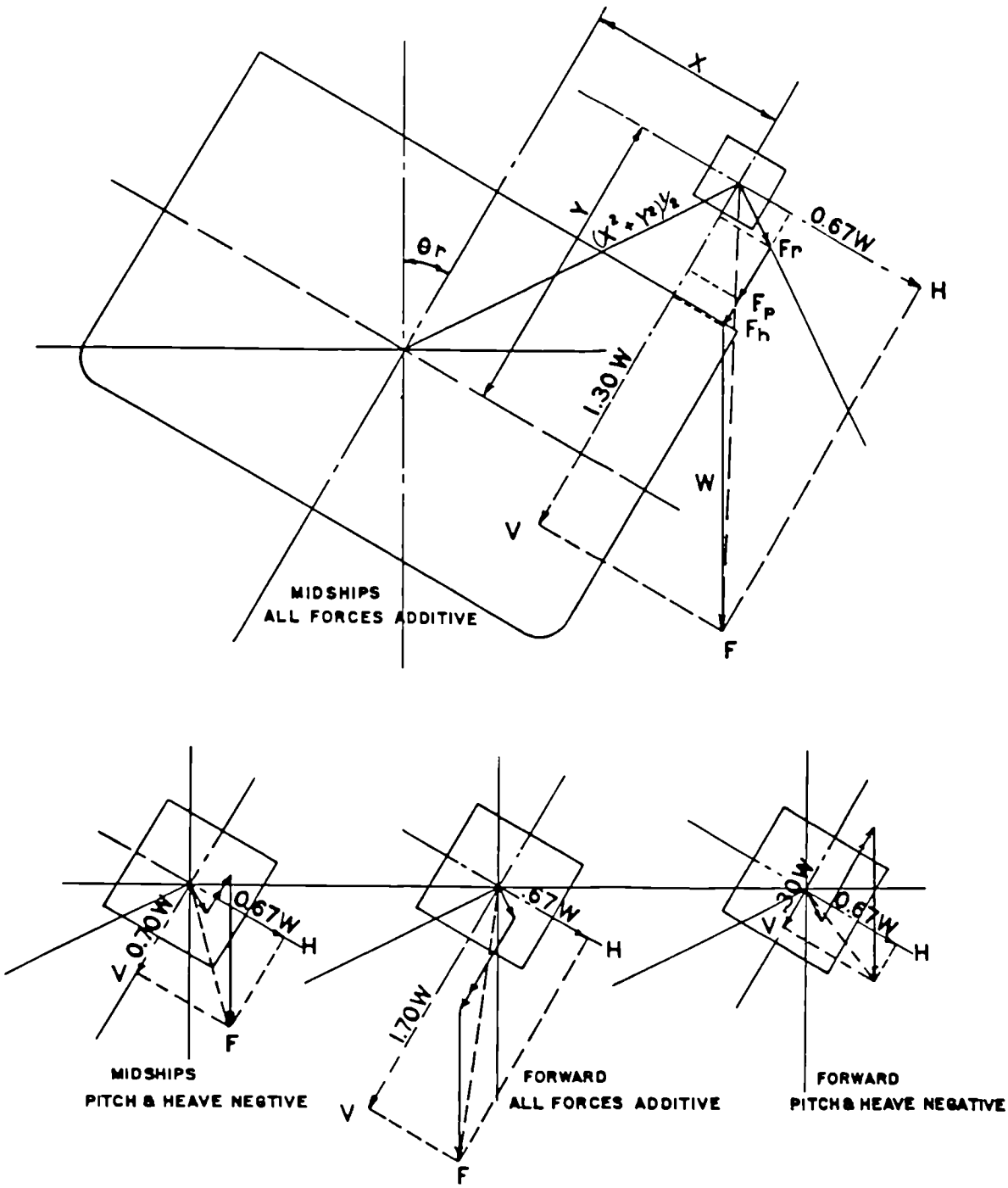


Figure 4.9 The forces acting on a deck-stowed container.

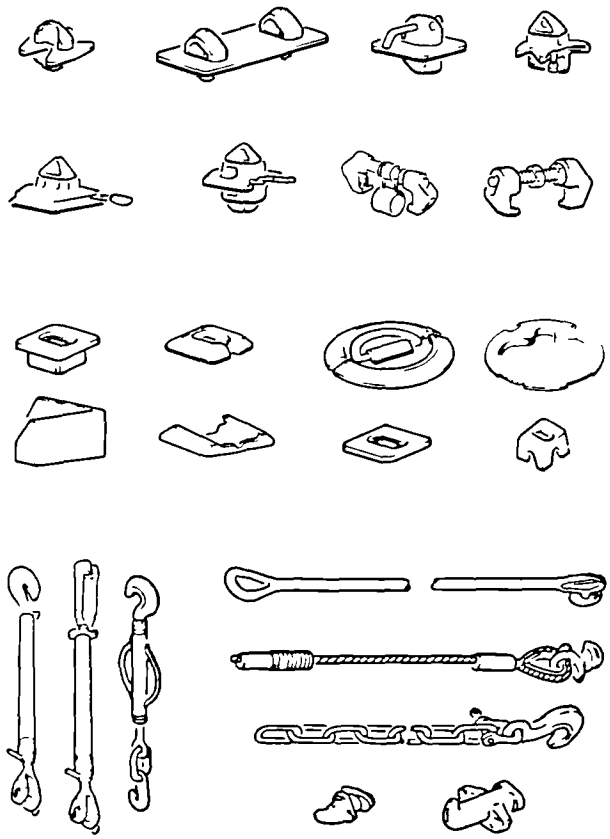


Figure 4.10 Some examples of container securing hardware.

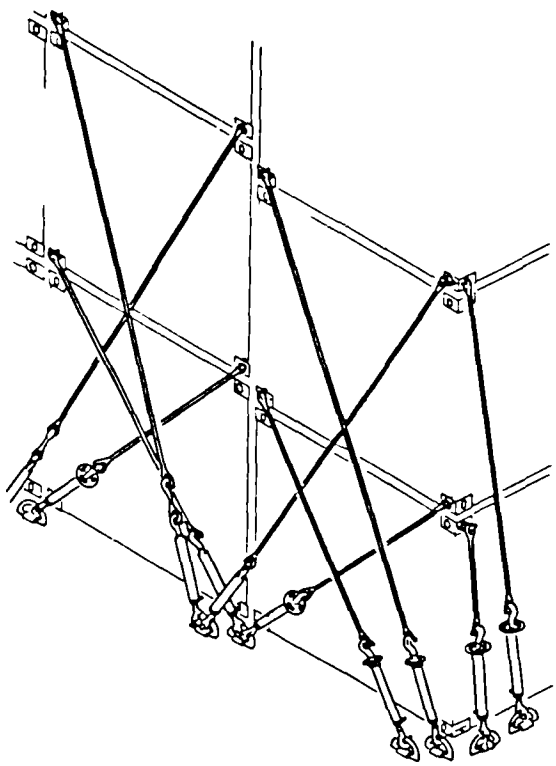


Figure 4.11 A typical lashing system for on-deck containers.

this proposal would appear to be an acceptable solution to the problem, there are a number of inherent disadvantages associated with the concept, as described in [4.14]. The most acceptable alternative method to deck lashing systems appears to be the use of cell guides or scaffolds on deck. A number of possible arrangements exist which are based upon the guide/scaffold concept as indicated below.

5.1.3.2.1 Scaffolds with horizontal sliding guide rails.

This system was adopted for a class of container vessels operated by Farrell Lines [4.15] and involves the use of traditional pontoon type hatch covers with scaffolds, fitted with movable guide rails, arranged transversely between the coamings. The hold containers are loaded in the normal manner with the movable guide rails being put into position, once the covers have been closed, to form cellular guides above the hatch covers.

5.1.3.2.2 Stacking frames and buttresses.

Another system, originally developed for the SL-7 class of vessels [4.16], uses horizontal stacking frames to secure tiers of containers, as shown in Figure 4.12 with the frames being attached to buttresses at the ends of the hatch. There are a number of disadvantages associated with this system such as the inability to stack containers of different heights in the same tier, and the need to lift off the frames in order to access the containers in the tiers below. This latter point will obviously result in severe penalties being incurred if any of the containers are overstowed, with access to containers in the lower tiers being required before those in the upper ones.

5.1.3.2.3 Cell guides with piggy-back hatch covers.

This system, as fitted to the ACL G3 class of vessel [4.17], utilise a system of cell guides with the hatch openings being closed by side-shifting piggy-back covers, as shown in Figure 4.13. The system operates by allowing access to the hold containers once the containers on at least two adjacent hatch cover panels have been removed. This then permits one panel to be shifted onto its neighbour to permit the unloading of the hold containers below, after which the panels can be moved again to reveal the next block of hold-stowed containers. Whilst it is necessary to remove loaded units before the panels can be shifted, it is possible to move the covers with up to three tiers of empty containers still in position.

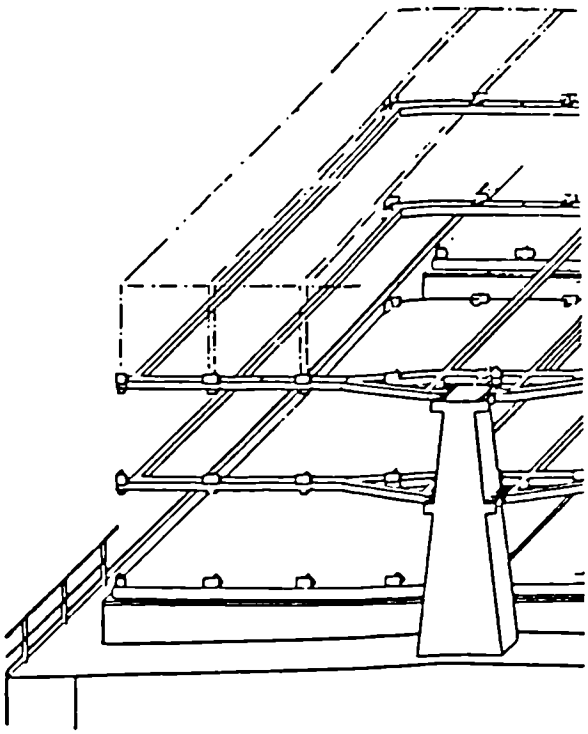


Figure 4.12 Horizontal stacking frame for securing on-deck containers.

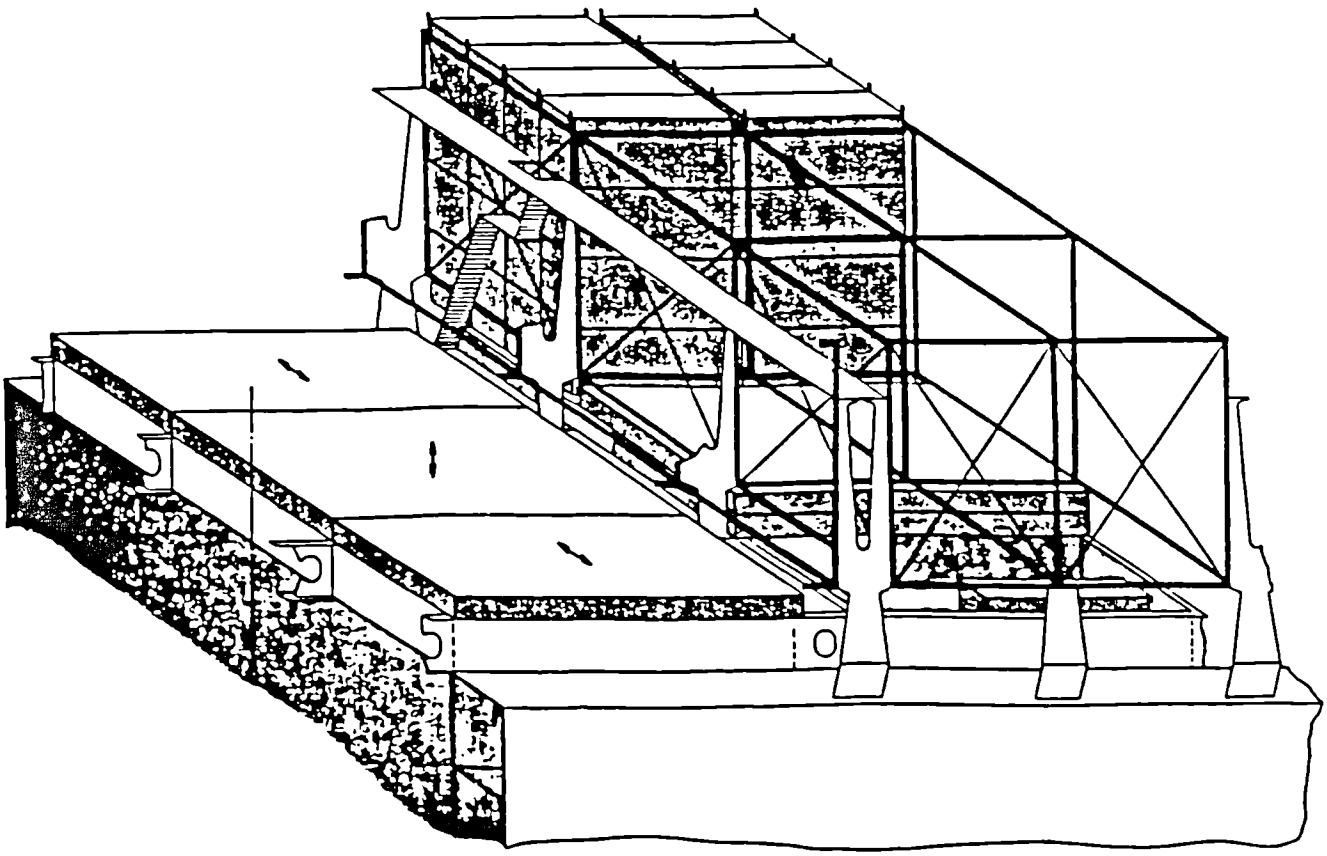


Figure 4.13 An on-deck cell-guide system.

5.1.3.2.4 Continuous guide rails with special covers.

With this system, the deck cell guides are a continuation of the hold guides with special hatch covers being used to close the openings. The hatch cover panels are simply lowered into position between the guides, in a similar manner to the containers themselves, with flip-flop type fittings being used at the corners to accommodate the guide rails. An example of this system is shown in Figure 4.14.

5.1.4 Cargo handling equipment.

As already mentioned, many cellular containerships do not carry their own cargo handling equipment but rely on the availability of shore-based equipment for the loading and discharge of the containers. Those vessels which do possess their own cargo handling equipment will usually be fitted with deck cranes of the pedestal or travelling gantry type.

Pedestal cranes, of the type shown in Figure 4.15, usually have a capacity of 35 tonnes and are electro-hydraulically operated to provide high speed operation and an excellent spotting capability. This lifting capacity will enable the crane to lift a fully loaded 40 foot container, and also permit the crane to lift a pontoon-type hatch cover panel to expose the under-deck stowage. One the of main disadvantages of using pedestal type cranes is the space occupied by the pedestal which results in the need for greater clearances between adjacent hatch ends. To reduce the space requirement of pedestal cranes, special slimline models have been developed for installation on containerships [4.18]. One proposal which does not require and increase in the between hatch clearances is the plug-in pedestal crane [4.19]. This type of crane, however, does cause some container capacity to be lost, but provides considerable operational flexibility as it can be removed or installed very quickly to suit the needs of the vessel on a particular voyage.

Travelling gantry cranes provide the most efficient means of shipboard container handling. This particular type of crane, as shown in Figure 4.16, runs on rails positioned outboard of the hatches and as such is able to travel practically the full length of the vessel, therefore removing the need for multi-crane arrangements. However the space required for the longitudinal rails does result in an increase in the beam of the vessel and the need to incorporate additional strength in the deck

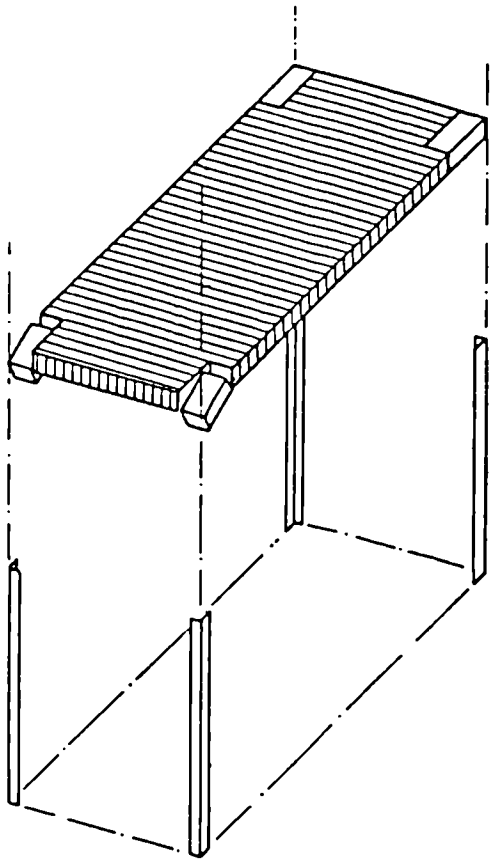


Figure 4.14 Continuous guide rails and flip-flop hatch covers.

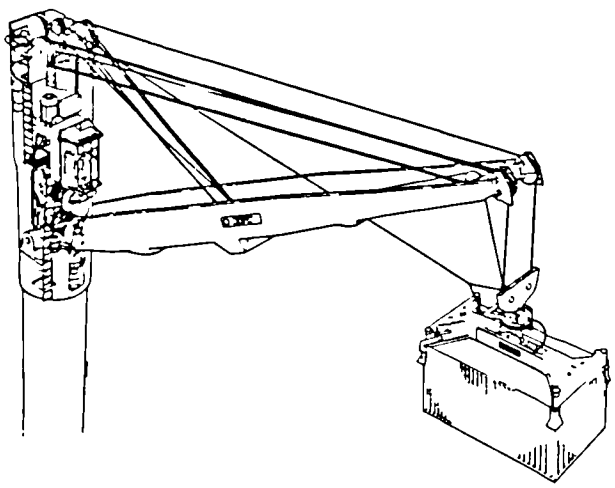


Figure 4.15 A typical container-handling shipboard pedestal crane.

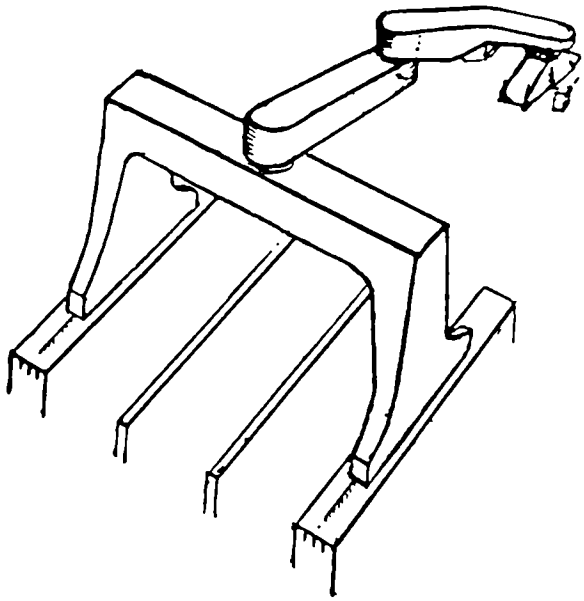


Figure 4.16 A typical container-handling shipboard gantry crane.

support structure can increase the complexity of the structural design problem. In addition the need for the crane to travel over the deck containers can limit the total number of tiers which can be stowed on deck. This type of crane does however give excellent cargo handling rates due to its high level of manoeuvrability and excellent spotting capability.

5.1.5 Hullforms.

The main characteristics of containership hullforms have changed over the years mainly as a result of the general reduction in speed brought about by increased fuel costs. These changes have mainly been in the areas of the block coefficient and forward and aft end shaping, in an attempt to reduce fuel consumption and hence reduce operating costs.

Containership after-bodies are generally characterised by wide transom sterns which provide added stability, increased hold volumes and increased deck areas, within a given set of main dimensions. The main disadvantages associated with these wide sterns are the increase in powering requirement due to the larger wetted surface area and hence frictional resistance, and the increased tendency to slam. Another significant disadvantage of this type of stern is the likelihood that the flat sections above the propeller will cause vibration due to the fluctuating pressure field associated with the propeller.

As previously mentioned, containership hullforms have been subjected to a number of changes caused by variations in the optimum operating speeds brought about by increased fuel costs. The early containerships were very high speed vessels (28+ knots) which required massive shaft powers. Such high powers could only be supplied using twin or triple screw configurations as shown in Figure 4.17. These hullforms experienced increased resistance due to the shaft bossings, brackets, etc., but enjoyed virtually vibration free operation due to the very low wake associated with the propellers operating in practically undisturbed flow. An advantage of the twin/triple screw arrangement was the inherent redundancy provided by the multi-engine installation. This provided the ability to maintain schedules in the event of a partial breakdown of the main propulsion machinery, and also allowed some maintenance to be carried out whilst the vessel remained in service. The ability to maintain schedules is obviously of great importance in an operation which is based upon

offering a fast and reliable service, involving a significant proportion of high value, often perishable cargo.

The forebody of containership hullforms will normally incorporate a bulb to promote the cancellation of the bow wave and therefore reduce wavemaking resistance although the shape and size of the bulb will have to be given special consideration as the relatively shallow drafts associated with containerships can lead to emergence of the bulb with the associated braking effect. Forebody sections will usually be V shaped in order to improve stability and increase deck area and under-deck container capacity. In an attempt to increase container capacity even further, many containership forms will incorporate significant flare in the fore body which also has a beneficial effect in that the chances of shipping water over the bow is considerably reduced.

Problems were experienced with the steering of some of the twin-screw variants, as described in [4.20], as the associated centreline rudders were not subjected to the increased flow normally expected when working directly behind a propeller, this resulted in virtually zero rudder response during low speed operation. This problem which could of course be avoided by the adoption of a twin rudder arrangement.

The general reduction in ship's speed and hence the drop in required power, enabled a single shaft system to be adopted for the propulsion of containerships. The location of a single screw on the centreline of a vessel, does however, limit the maximum diameter of propeller which can be installed and therefore requires that the blade area of the propeller is greater than on a twin screw system. This in turn results in reduced propeller efficiency, which, when combined with the fact that the propeller is operating in a far from perfect wake, can result in an increase in delivered power for a given speed over the twin or triple screw form. The main advantage of the single screw installation is that first cost and maintenance are considerably less than for the multiple screw arrangements with their associated multi-engine installations. Examples of typical single screw containership hullforms are shown in Figure 4.18.

In view of the relative reduction in containership speeds in recent years, it is unlikely that multiple-screw configurations would be adopted for modern vessels as the power requirements of even the biggest of the modern vessels is well within the capability of the presently available direct drive, slow speed diesel engines, as illustrated by the selection of such an arrangement for the C-10 class of vessel described in [4.11]. The

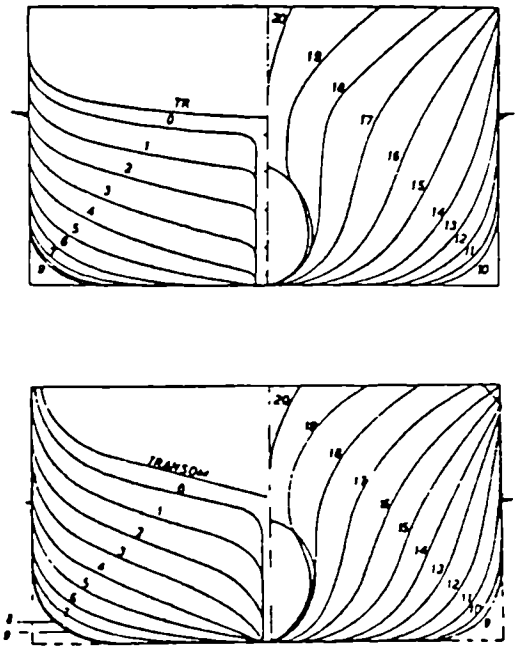


Figure 4.17 Typical twin-screw containership hullforms.

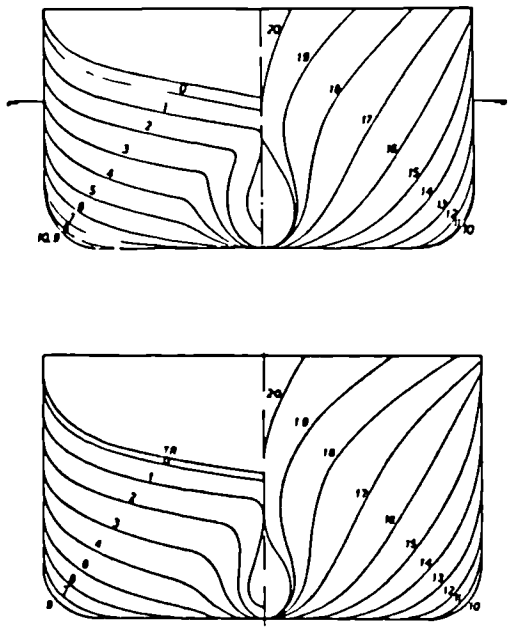


Figure 4.18 Typical single-screw containership hullforms.

57,000 bhp output of the Sulzer engines specified for these vessels could previously have only been supplied by a multi-engine diesel or steam turbine arrangement. With fuel prices likely to remain relatively high, it is quite unlikely that future containership speeds will increase much above their present level and cause power requirements to exceed the output of the larger slow speed diesel engines. It is therefore reasonable to assume that the vast majority of containership hullforms will in the future be of the single screw type.

5.1.6 Structural design.

The main requirement of the structure in any type of vessel is that it can adequately withstand the forces, both local and global, produced by the ship mass, its distribution, its ship motions and the environment. The containership is no exception to this requirement, but the nature of the cargo carries tends to lead to a number of unique problems when the general and detailed structural layout is being considered.

5.1.6.1 General structural arrangement.

The main aim of the containership concept is to carry the maximum number of containers within the smallest possible envelope. In order to achieve this goal the size of hatchways must be as large as possible with no structure protruding into the cargo spaces. This requirement results in the hatchways being around 80% of the breadth of the vessel with perhaps only a single frame space between adjacent hatches in the longitudinal direction.

The transverse bulkheads in containerships perform two important functions apart from the usual one of providing a means of watertight subdivision, as indicated below:

- They provide a rigid structure to which the cell guide system is attached and therefore absorb the dynamic forces transmitted to the cell guide structure by the containers due to the motions of the vessel.

- They withstand the static and dynamic forces, resulting from the containers stacked several tiers high on deck, which are transmitted to the bulkheads through the deck beam and girder arrangements.

In order that the bulkheads are of sufficient strength to perform the above duties,

they will usually be of a double skin construction, similar to a vertically oriented double bottom, with stringers to provide support in place of 'tween decks. Vertical webs will usually coincide with the cell guide structure to absorb the loads transmitted by the guide rails.

One of the main problems associated with the normal structural arrangement of containerships is that resulting from the lack of torsional strength caused by the large hatch openings ([4.21], [4.22]). In order to alleviate these torsional problems, deep deck "box-girders" will sometimes be used to reduce the width of individual hatch openings. The use of such girders will result in a multi-hatch arrangement as shown in Figure 4.19.

The strip of strength deck outboard of the hatches will usually be in the region of 10% of the beam of the vessel, a fact which can lead to problems with longitudinal strength due to the imbalance between the bottom and deck structures and the corresponding low neutral axis. This problem can usually be overcome, however, by the use of box-girder arrangements and higher tensile construction materials in the deck region.

As can be seen from Figure 4.19, the midship section of a typical containership is characterised by a twin-hull type of side structure. This double skin arrangement contributes significantly to both the longitudinal and torsional strength of the vessel, and also provides a means of the vessel with the effect of absorbing the dynamic and static forces produced by the hold containers. Loading from the on-deck containers is also transmitted to the side structure via the hatch covers and hatch-side coamings. Another feature of this double-skin arrangement is the creation of side spaces suitable for use as fuel oil or water ballast tanks.

Within individual cargo holds there will usually be transverse web frame type structures positioned between adjacent hatches. These structures are similar to the transverse bulkheads in construction, but lack the associated watertight plating. The main purpose of these members is to provide support for the hatch end coamings and absorb the loadings transmitted through them.

The double bottom structure of containerships has to be particularly strong in order to absorb the high loadings from the side and bulkhead structures, and the concentrated loadings from the hold container stacks. The double bottom structure shown

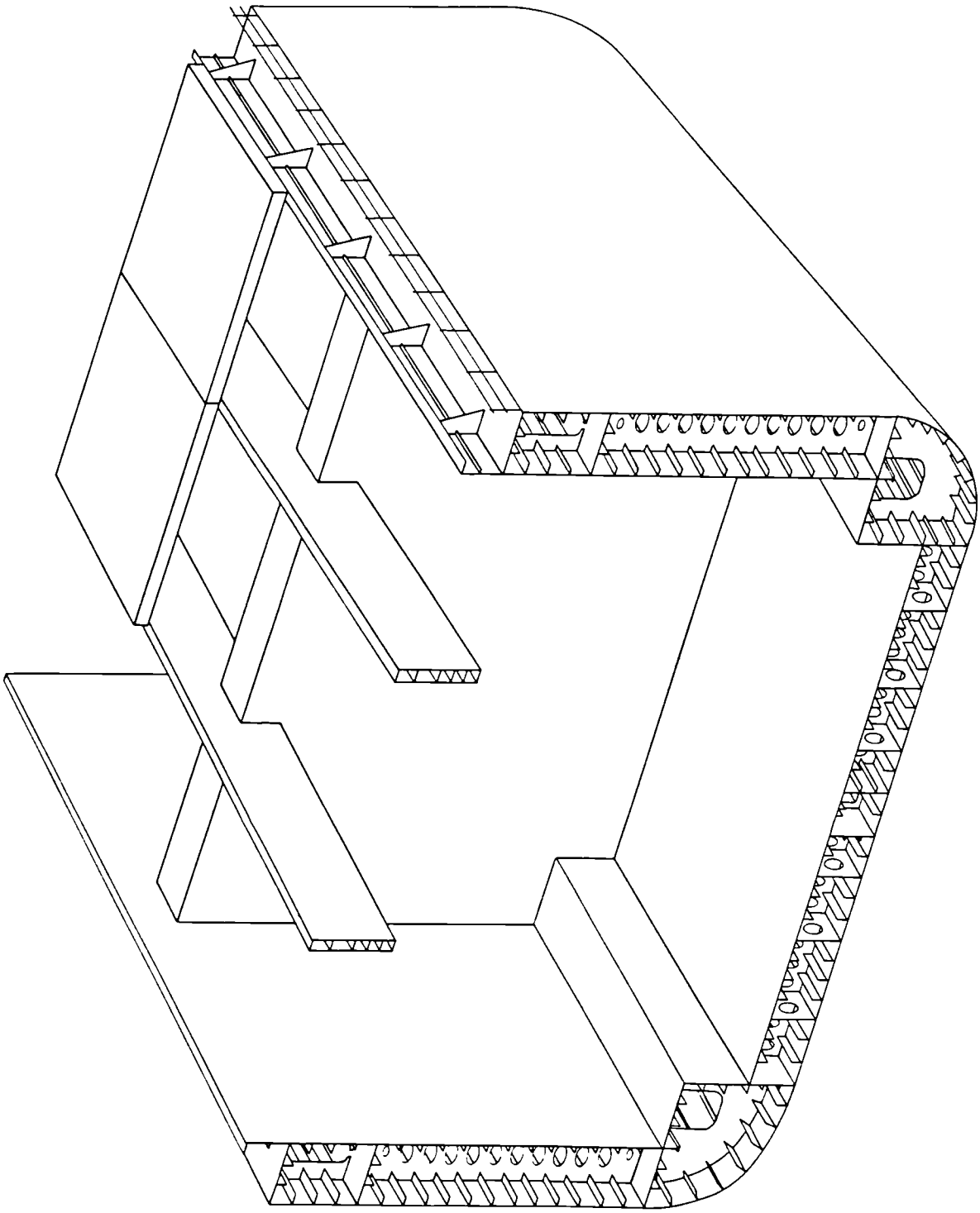


Figure 4.19 A typical containership midship structural arrangement.

in Figure 4.19 illustrates the usual arrangement of girders used to distribute the load both from the connecting structure and the container stacks. As previously indicated, containership double bottom structures tend to have a high cross sectional area and hence a high inertia when compared to the deck structure, which can in turn lead to overall strength problems.

5.1.7 Trim.

Containerships are by tradition relatively high speed vessels and as such will usually be associated with fairly fine hullforms. The fineness of these forms together with the distribution of mass tends to cause trim problems during vessel operation. Small waterplane areas at light drafts cause containerships to be very sensitive to changes in mass distribution during the course of a voyage as caused by fuel oil being used and ballast being added for stability purposes. It should be noted that the distribution of ballast and fuel tanks required to give acceptable trim characteristics over a range of non-homogenous and departure/arrival loading conditions conditions, is not necessarily the best when considering other aspects of the design such as longitudinal strength. Careful consideration must therefore be given to the development of the best arrangement of tanks to be incorporated in the vessel from both trim and strength aspects.

5.1.8. Stability.

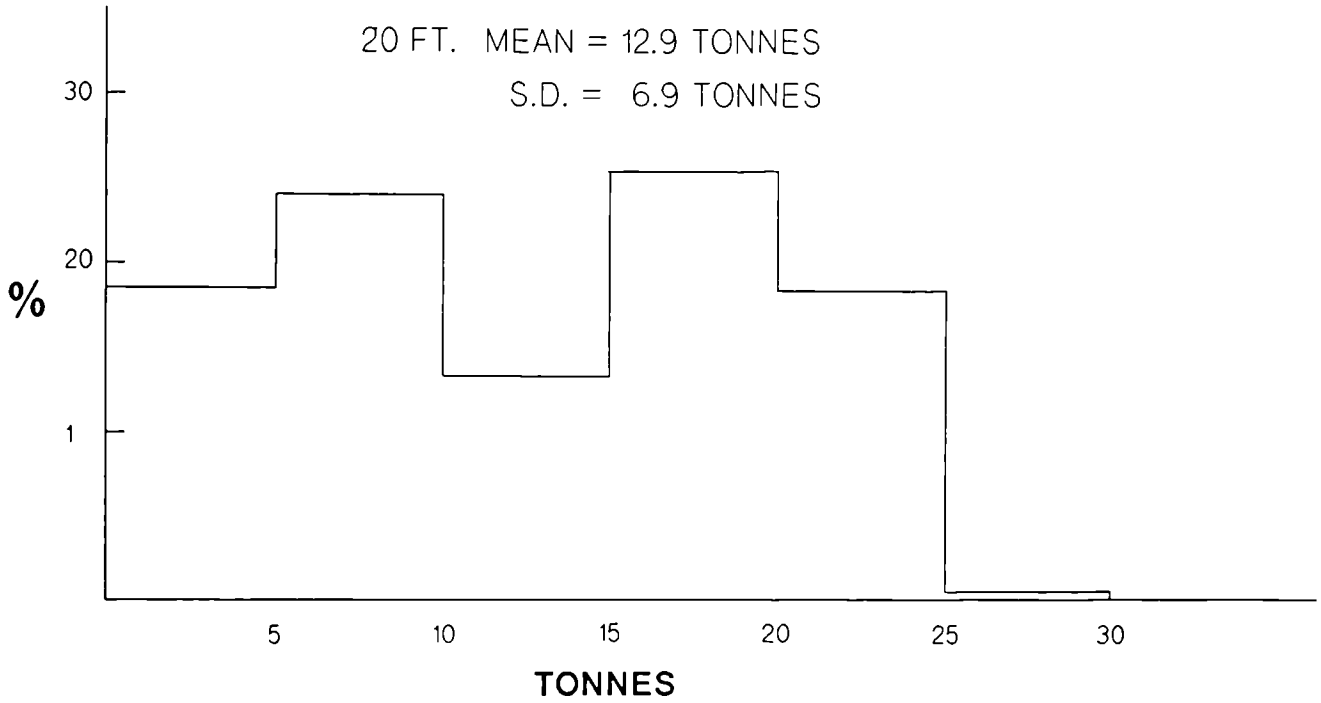
The stability of containerships is perhaps the most important aspect of their design. The nature of the cargo carried in container vessels tends to make the stability of this type of vessel of prime concern to both the ship designer and the ship operator. The vertical centre of gravity of the complete cargo block tends to be very high as a consequence of carrying considerable numbers of containers on deck, with the result that containerships will inevitably have to be operated with considerable amounts of ballast. Although the carriage of ballast is common practice in most ship types, (where ballast is carried when the vessel is without cargo), the containership is in the relatively unique situation of being designed for the carriage of ballast even in the normal loaded departure condition. In fact it is not unusual for containerships to start a loaded voyage with up to 25% of their total displacement being made up of water ballast, with some vessels even being designed with some degree of permanent ballast [4.16]. The main cause of the need to carry such large amounts of ballast is the

limitation imposed on the breadth of most vessels imposed by the requirement to negotiate the Panama Canal with the associated detrimental effect on stability. The advantages to be gained from exceeding the Panamax beam [4.11] are typified by the vastly reduced requirement for ballast water in most loaded conditions with the added advantage of being able to carry containers in five tiers on deck.

Although container units are designed to carry fairly high payloads (20.3 tonnes in the case of the twenty foot unit, and 30.5 tonnes in the forty foot container), an analysis of the actual masses carried on all container trades reveals that the average container masses are in fact 13.2 tonnes per 20 foot unit (standard deviation 5.6 tonnes) and 16.2 tonnes per 40 foot container (sd 5.9 tonnes) [4.23]. It can also be demonstrated that the variation in the actual masses being carried in containers is quite considerable. Figure 4.20 shows in histogram form the distribution of container masses on a particular voyage of a cellular container vessel from Europe to the Far East [4.24], with Figure 4.21 showing the variation in average container mass on a number of different voyages for the same class of cellular containership.

In order to minimise the amount of ballast which has to be carried on a particular voyage, the available containers will normally be loaded so as to give a tapering of the mass distribution in the vertical plane. This arrangement has the effect of locating the heavier containers in the bottom tiers with the lighter and empty units being carried on-deck with the net result that the height of the overall vertical centre of gravity of the cargo is reduced. Figure 4.22 illustrates the use of this tapering effect, to reduce the overall cargo vertical centre of gravity on a number of voyages of the particular class of cellular containership [4.24].

In view of the fact that the random nature of the mass distribution of containerised cargo is clearly going to result in non-homogenous loading arrangements, it is rather surprising to note that containership design proposals are presently developed and analysed on the basis of an assumed homogeneous loading arrangement, this being a simplified model which can lead to the development of inflexible designs. This can lead to container vessels being built which are unable to cope with the variation in loading arrangements which are encountered in practice, without incurring significant penalties of excessive ballast requirements, etc. Ship operators are therefore of the opinion that a more realistic model of the containership concept should be used which reflects the true nature of the conditions under which the vessel is to operate,



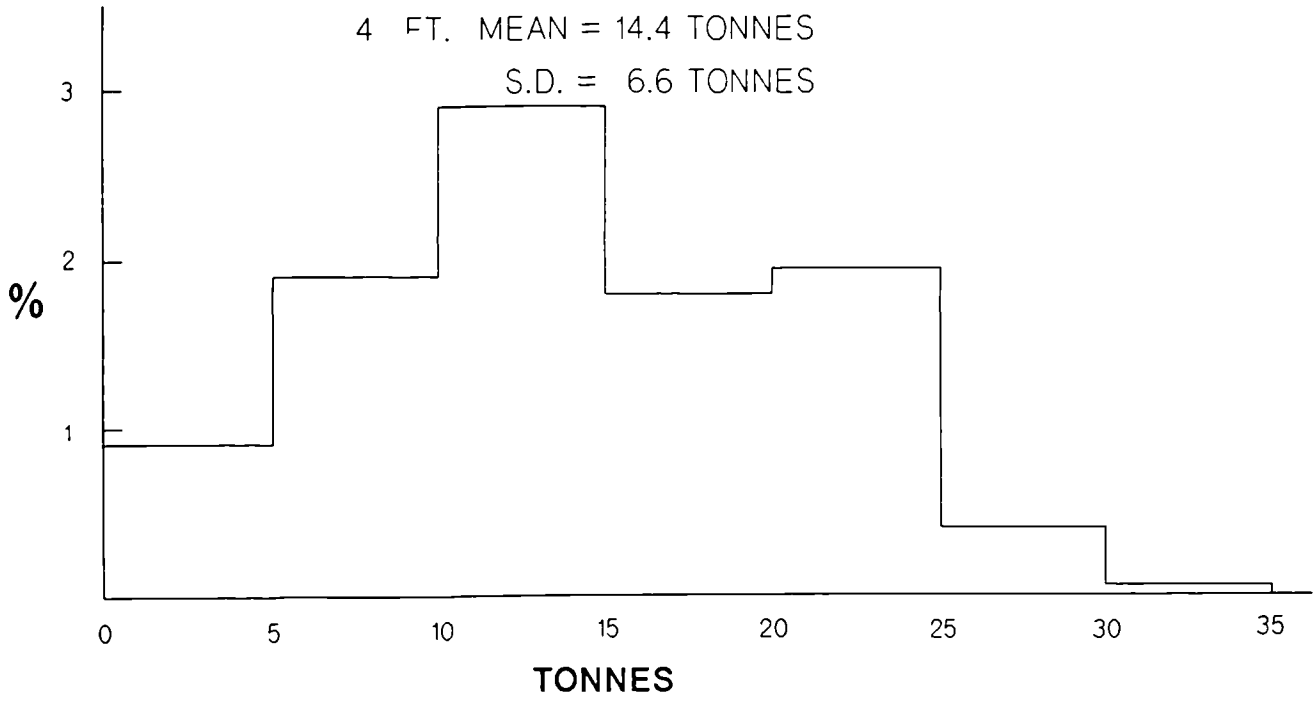


Figure 4.20 Distribution of container masses on a single voyage.

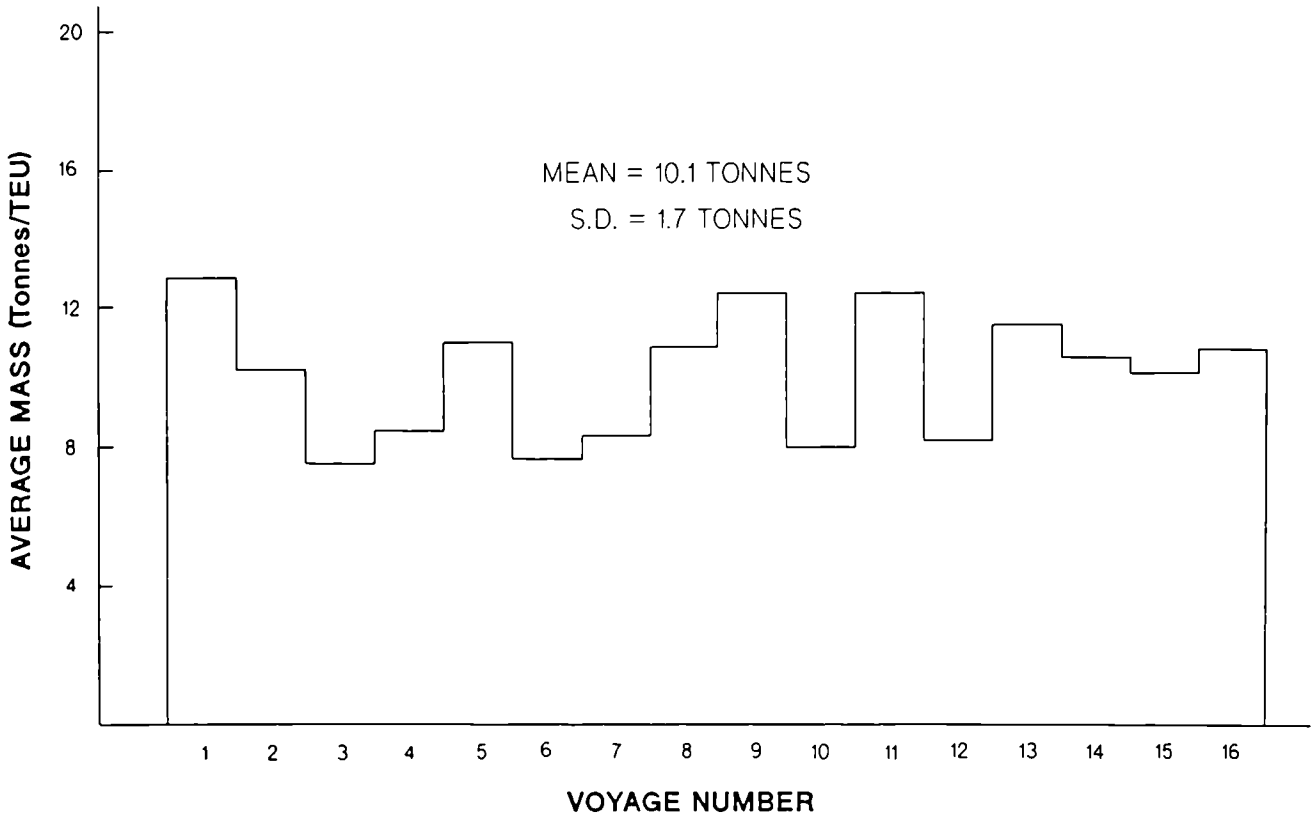


Figure 4.21 Voyage analysis of container average masses.

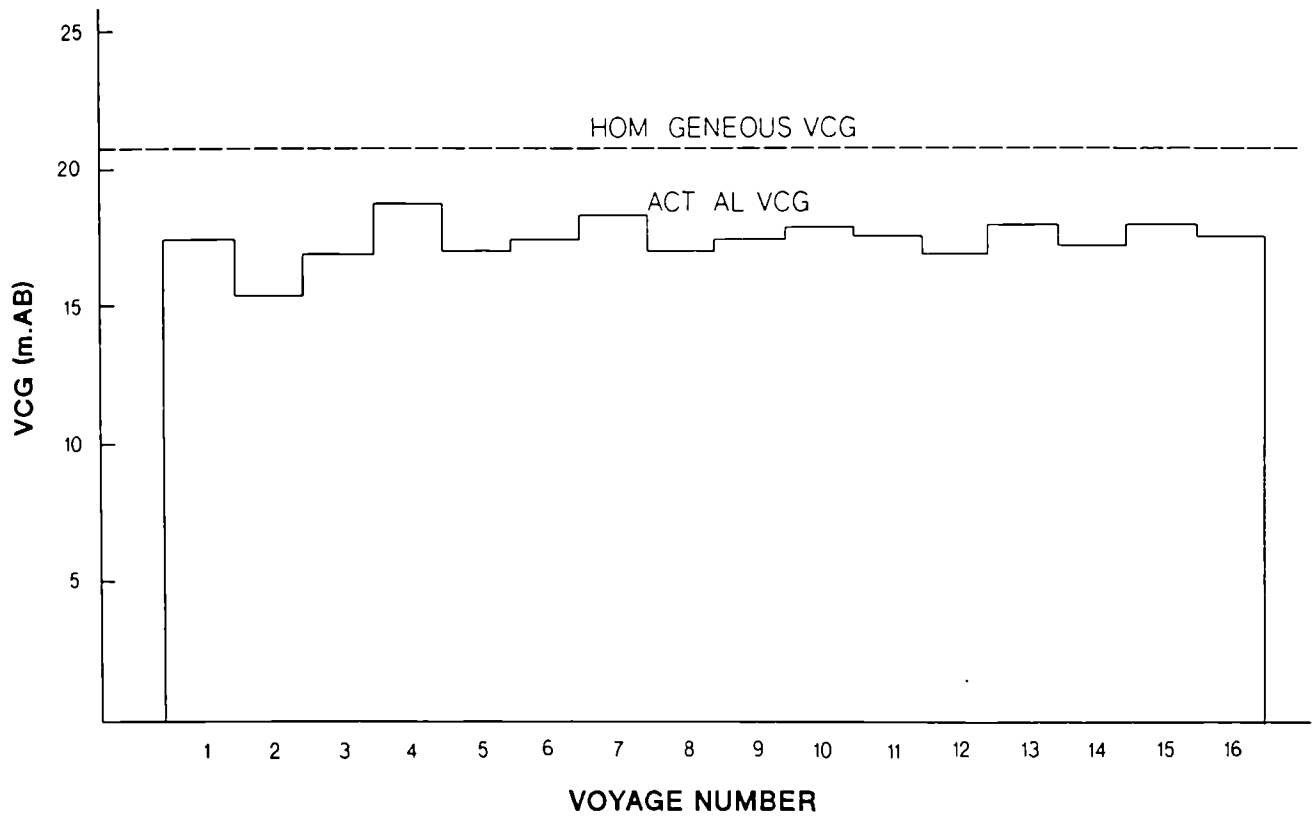


Figure 4.22 The effect on vertical centre of gravity of container mass distributions.

thus enabling the inherent flexibility of the proposal, in terms of its ability to operate under a wide range of non-homogenous loading conditions, to be demonstrated.

6. The containership as a design problem.

The previous sections of this Chapter have described in some detail the main aspects concerned with the development of containership design proposals. As can be seen from the preceeding text, the containership has associated with it all of the usual design considerations covering areas such as hullform design, powering, and so on, but also introduces a number of fairly unique problems. Being a volume dependent type of vessel introduces the requirement to ensure that the best possible use is made of the available space in order to maximise the amount of cargo carried. The fact that the cargo units come in various sizes and forms, some with quite specific requirements in terms of stowage and support services, can lead to significant difficulties when attempting to develop a design proposal which possesses sufficient flexibility to operate with a variety of cargo types.

The structural integrity of containerships is also a major concern, with the local and overall strength problems associated with the carriage of containerised cargo.

Perhaps the most important aspect of containership design, and one which up until now has been largely ignored, is that associated with the completely random nature of the masses of the individual containers which have to be accommodated in a vessel. The true flexibility of a vessel can only be determined by modelling these non-homogeneous loading conditions with their associated implications for ballast requirement and hence vessel profitability.

In view of the above points, it was considered that the containership concept was one which was ideally suited to the application of knowledge based systems, with the advisory capability of such systems being able to generate proposals based upon much more realistic models than had previously been possible. These models would reflect the true level of complexity associated with containership design, and would not only be able to consider the technical aspects of the containership concept, but would also be in a position to assess the economic feasibility of containership operation.

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CHAPTER 5

The Containership Design Knowledge Base.

SUMMARY.

This Chapter describes the INCODES-compatible knowledge base which has been developed for the generation and analysis of containership design proposals. The content and structure of the knowledge base are described in some detail. The various procedures developed to form part of the knowledge base are described, including those for the generation of main dimensions, the development of hullform descriptions, the definition of general arrangements, and the analysis of the various aspects of containership design proposals. In particular, the unique way in which the problems associated with the investigation of containership loading arrangements are approached, is discussed.

Above all, the flexibility and consistency of the approaches adopted throughout the system are made apparent.

1. Introduction.

Having considered the problems associated with the design of containerships, the next stage in the development of the conceptual containership design system was to define the methodology to be adopted as the basis of the system. It was also necessary to define the structure of the knowledge base which was to be combined with the INCODES expert system shell to form the expert containership design system. As previously mentioned, the adoption of an expert system approach in the development of the design system allows an effective design aid to be provided which was able to offer an advisory service to the user based upon in-built expert knowledge.

As can be appreciated, the general capability of any expert system is determined by

the quality of the associated knowledge base. In the case of the concept ship design system being described here, it was required to develop a carefully structured knowledge base which could be attached to the previously described INCODES expert system shell to produce the expert design system. Referring back to Chapter 2 of this thesis, the main problems associated with the development of expert system applications are nearly all concerned with the process of obtaining the information required to construct the application-specific knowledge base. This process of extracting knowledge from either human or non-human sources is often called knowledge elicitation, and is of fundamental importance in the development of expert system applications. As previously mentioned, the success or otherwise of a proposed application will be completely dependent upon the quality and scope of the knowledge extracted from the relevant sources. The importance of the knowledge elicitation process has been appreciated ever since expert system applications were first developed, and has in fact become an individual area of study with considerable research effort being put into the development of the various knowledge elicitation techniques.

1.1 Knowledge elicitation techniques.

It is widely claimed that knowledge elicitation is the bottleneck in the building of expert systems. This is due in the main to the following points:

- There is no way of determining which of the available knowledge elicitation techniques will be best suited to a particular problem. This can only usually be done by trying a number of techniques until the most suitable is found.

- As a result of this trial and error approach, the knowledge elicitation stage of expert system development can often be long winded and very time consuming.

- The problem of non-cooperation on behalf of the domain experts tends to make the task of the knowledge engineer much more difficult.

- The knowledge engineer can often be misled by the domain experts in their attempts to justify the methodology adopted and decisions made

in the problem solving process.

In view of the above points, a number of knowledge elicitation techniques have been proposed and developed as expert system building tools. Each of the techniques in general use have their associated advantages and disadvantages, features which make them more useful in some cases than others. A brief description of each of the most common of the available techniques is given below; with a more detailed discussion of the techniques being given in [5.1], and examples of their application being given in [5.2].

1.1.1 Forward scenario simulation.

The basis of this technique is a face-to-face interview with the relevant expert, with the expert being asked to solve a series of hypothetical problems in the particular domain. During the problem solving process the expert is asked to verbally explain the reasoning behind each of the decisions he makes.

One of the main advantages of this technique is that the knowledge engineer can set the limits of the elicitation, thus avoiding the limitations which occur when the expert is allowed to communicate the way in which common problems are solved.

The main disadvantages associated with this technique are those resulting from trying to elicitate knowledge from an expert who is unable to communicate effectively, and one who is susceptible to erratic justification which can result in spurious decision rules in the knowledge base.

1.1.2 Protocol analysis.

This technique is perhaps the most simple, and is also one of the most effective. It involves the knowledge engineer simply recording the activities of the expert by audio or video tape or by taking written notes, and analysing the relevant activities to derive protocols. These protocols are further analysed to produce meaningful rules which can be included in a knowledge base.

The main advantage of this technique is that the expert is being observed actually solving problems, which can be more enlightening than having the expert justifying his decisions while attempting to solve hypothetical problems as described previously.

One of the major limitations of this technique is the one caused by the lack of experience of the knowledge engineer in the particular problem domain. This can lead to the knowledge engineer overlooking the differences in the various problem solving procedures used by the expert. Another disadvantage of the technique is that of only observing the procedures followed in the solution of normal day to day problems, without ever encountering the rare, but equally important situations.

1.1.3 Goal decomposition.

This is the collective name for a group of knowledge elicitation techniques which includes the *20 questions* and the *laddered grid* methods.

1.1.3.1 20 questions.

This method involves the engineer composing a set of solved problems with the expert being required to ask questions of the engineer in order to establish the problem solution. This technique has the effect of revealing exactly what information the expert requires in order to arrive at a solution, and also the order in which the expert asks the questions can indicate the structure of the required problem solving process. The only real problem associated with this technique is the fact that the knowledge engineer obviously has to have some knowledge of the domain, and must also have enough information available to be able to answer all of the possible questions from the expert.

1.1.3.2 Laddered grid.

If it can be assumed that there is a clear hierarchical structure to a problem domain, then the laddered grid technique of knowledge elicitation can be applied. The technique involves placing the expert at a particular point in the problem hierarchy and asking questions about the levels above and below the current one. By moving around the decision space, a complete picture of the relationship between the elements of the hierarchy can be obtained.

Although this technique can be used to rapidly build up a picture of the complete domain, it can only be successfully employed in situations where the domain can be expressed in an ordered, hierarchical form.

1.2 Knowledge elicitation in the context of the conceptual ship design system.

In the context of the conceptual ship design system being considered here, it was first required to identify the available possible sources of relevant expertise and knowledge to be used to develop the expert system knowledge base. Consideration of this aspect of the system development resulted in the identification of a number of main commercial activities which were involved in the areas of containership design, construction and operation. These main groups can be summarised as follows:

- Shipbuilders.
- Marine consultancies.
- Ship operators/owners.

With regard to the first activity listed above, the shipbuilding yards of British Shipbuilders Limited provided an obvious source of knowledge and expertise in the area of containership design, in addition to the section of the Corporation concerned with product development. Marine consultancies offered a potential source of considerable information regarding the design of containerships, as they provide a service to shipowners in terms of assessing the various design proposals developed by competing shipbuilders.

Ship operators/owners provide an obvious source of expertise concerning aspects of containership design as they have first-hand experience of the consequences of decisions made at the design stage.

A decision was made to approach the subsidiaries of British Shipbuilders Limited on the Clyde and on the Wear as these were either involved in the design and construction of container carrying vessels or were actively involved in the preparation of detailed tenders for containership tonnage.

An examination of a number of marine consultancies indicated that one in particular, Ocean Fleets Limited, were currently involved in the supervision of the design and construction of a series of very large containerships for overseas owners. This fact, together with their own experience of operating ships, made them ideal candidates for participation in a knowledge elicitation exercise.

P & O Containers Limited were identified as a company operating an existing fleet of pure container carrying vessels, and were also in the process of having two new large containerships built in a Japanese shipyard. The company therefore provided the opportunity to obtain information regarding operational aspects of the containership concept together with additional information concerned with the specification and design of modern container carrying vesels.

With the above sources of knowledge and expertise concerning the design and operation of container vessels identified, an assessment of the available knowledge elicitation techniques (as discussed in Section 1) was carried out to determine which was most suitable for the purpose of extracting knowledge suitable for inclusion in the containership design knowledge base.

As a result of this examination, it was decided that the forward scenario simulation technique would be the most suitable for the current application. The size of the containership design problem and the timescale associated with the preparation of design proposals virtually eliminated the possibility of using knowledge elicitation technique such as protocol analysis, and the laddered grid.

Due to the size and complexity of the problem being considered, it was decided to divide the overall problem into a number of sub-problems each concerned with a specific aspect of the containership design problem. For each of these problems a number of possible scenarios were constructed which required the experts to explain the lines of reasoning being followed when solving the particular sub-problems. These problems covered the three main areas which have to be considered in the containership design process. These main areas, together with some of their associated parameters, are shown in Figure 5.1.

Using the generated sub-problem structure as a basis, interviews were conducted with personnel from the above mentioned organisations to determine the information required in order to build the expert system knowledge base. The information obtained was used to produce the heuristic based production rules contained in the knowledge base, and was also used to form the basis of the many external analysis procedures developed to form part of the system.

The following sections of this Chapter describe in some detail the actual structure and content of the containership design knowledge base in terms of both the heuristic

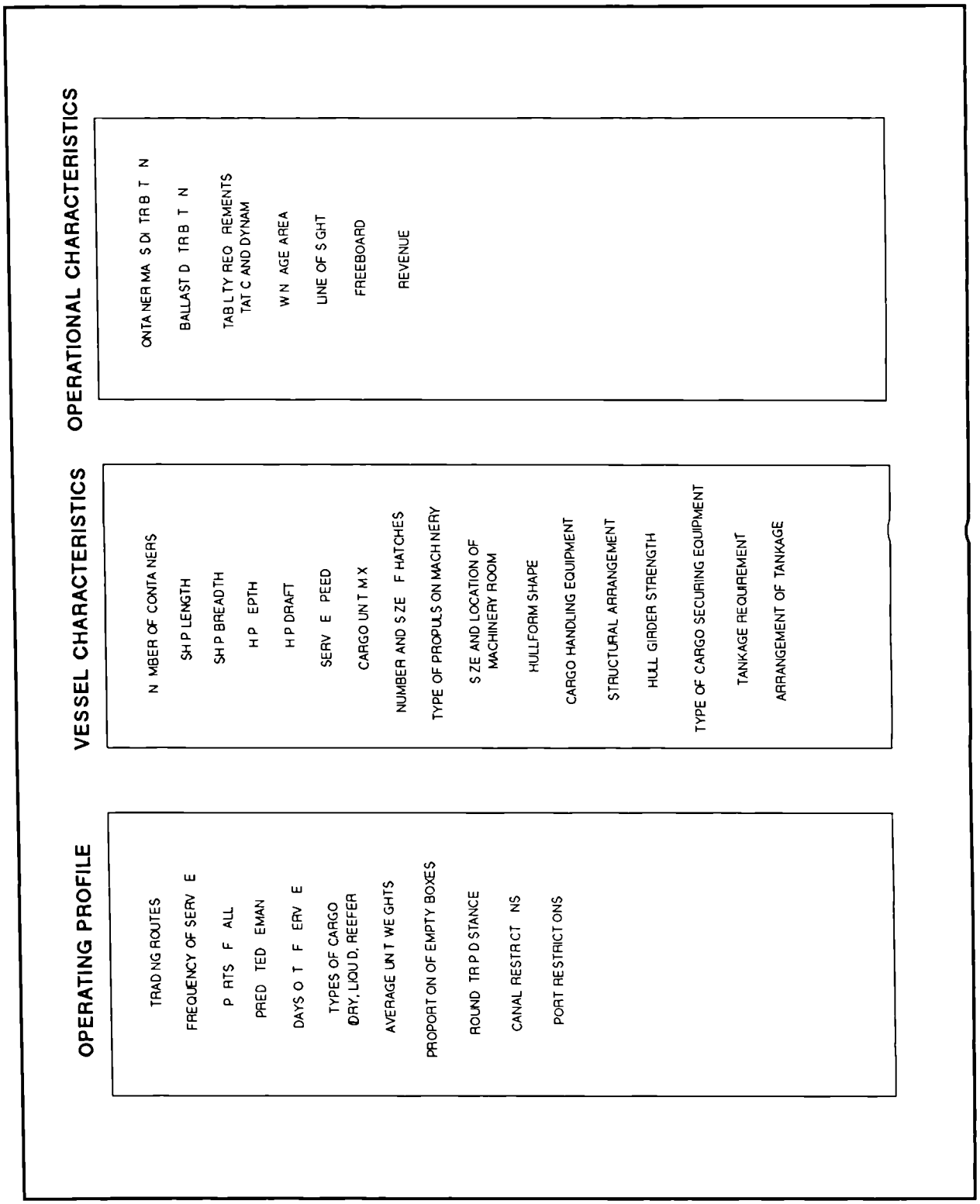


Figure 5.1 The main considerations in the containership design process.

type knowledge and the procedural and design analysis type knowledge contained therein.

2. Structure and content of the knowledge base.

The domain knowledge obtained from the sources described in the previous section was utilised to form the basis of the containership conceptual design system. The various aspects of containership design methodology were examined and the basic schema of the design system was produced, as shown in Figure 5.2. As can be seen from the diagram, the containership design problem can be expressed in terms of a number of separate sub-problems concerning areas such as dimensions estimation, form characteristics, hullform design, general arrangement design, and so on. In terms of the containership design knowledge base, the knowledge and expertise relevant to each of these areas, obtained from the knowledge elicitation exercises, was applied to the construction of the complete knowledge base. The scope and structure of the knowledge base is described in the following sections by examination of each of the sub-areas shown in Figure 5.2.

2.1 Estimation of preliminary main dimensions.

As was previously described in Chapter 4, the main dimensions of a containership are direct functions of the sizes of the cargo units to be carried by the vessel. As a result of this relationship between the dimensions of the vessel and the dimensions of the container units, any attempt to obtain a relationship between vessel capacity and the main dimensions will not result in the development of continuous functions similar to those proposed for the estimations of the main dimensions of deadweight dependent types of vessel [5.3], but will result in a type of stepped function. The fact that containerships carry a significant proportion of their overall capacity above the upper deck cannot easily be reflected in a simple capacity-size relationship. The problems associated with determining an estimate of the main dimensions of containerships have been considered on a number of previous occasions with a variety of design methodologies being proposed. One such methodology [5.4] recognised the need to associate the main dimensions of the vessel to the arrangement of containers in terms of the number of bays, tiers and rows to be accommodated both above and below the upper deck. The procedure utilised a system of *zones* which related capacity to combinations of numbers of bays, tiers and rows of containers, from which the

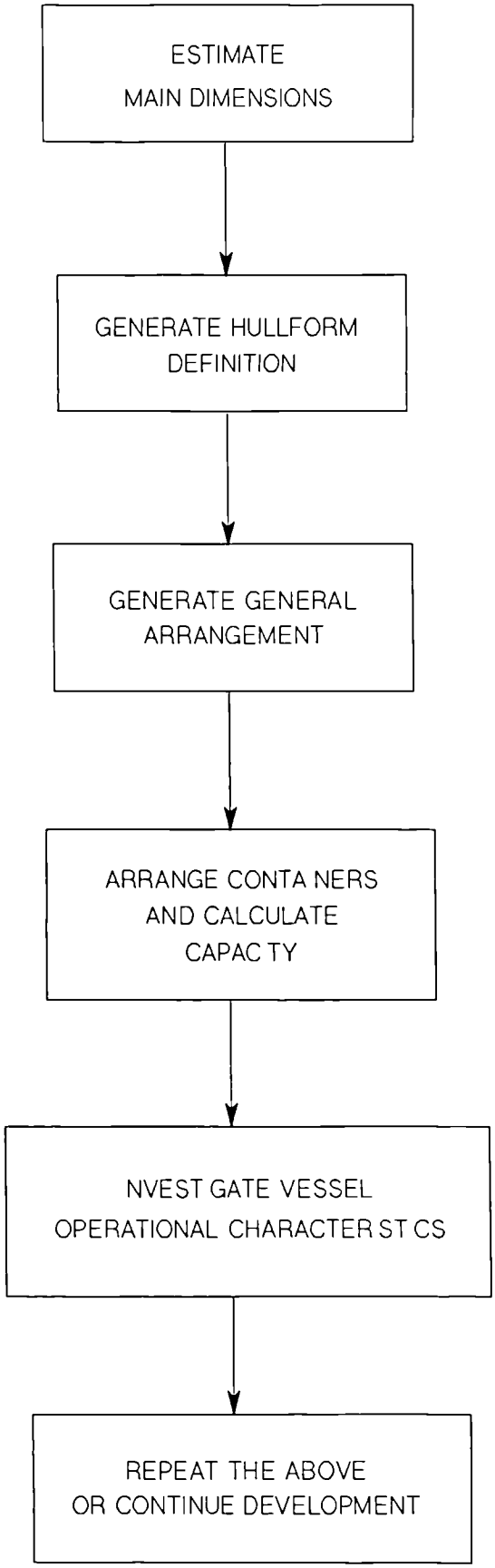


Figure 5.2 The main steps in the containerhsip design process.

dimensions of a vessel could be determined which provided the required capacity. The variation in vessel capacity, for a given arrangement of bays, tiers and rows of containers, as caused by different hull shapes and fullnesses, was taken into account by the application of a *shape factor* which was a function of vessel fullness at a pre-defined proportion of the depth.

Although providing a reasonable estimate of the main dimensions of a design proposal, the method proposed by Bentley, in common with most of the other available procedures for conceptual containership design, does not provide for the assessment of the effect of relatively minor modifications to the design specifiction. For example, the effect of the incorporation of alternative container securing systems cannot be demonstrated, and the methodology is also unable to properly address the question of water ballast capacity and its effective usage.

The method of estimating vessel preliminary dimensions developed by the author for inclusion in the containership conceptual design system described here, utilises basis vessel information to develop an estimate of the number of bays, tiers and rows of containers likely to be required both below and above the main deck in order to satisfy the specified required capacity. The most suitable basis vessel is selected from those available so that it most closely resembles the proposed design vessel in terms of overall capacity and operating speed. The available basis vessels are held in a form of database on the host computer system, with the particulars of the basis vessels being modified, deleted or added to, as and when required by the system user or administrator.

Once the most suitable basis has been selected from those available, an examination of the relevant particulars of the basis in respect of its arrangement of containers, both below and above deck, is carried out. From this information a shape factor is determined which relates the actual capacity of the vessel to the theoretical capacity as determined by the number of bays, tiers and rows of containers, as indicated below:

$$\text{shape factor} = \frac{\text{actual capacity (below or above dk).}}{\text{(No. of bays x no. of tiers x no. of rows)}}$$

Assuming that the design speeds of the basis and design vessels are similar and the

total capacities of the two vessels are reasonably alike, then it is considered reasonable to assume that the shape factor for the basis vessel can also be applied to the design proposal. The capacity of the design proposal can therefore be determined from the following:

capacity (total) = capacity (below deck) + capacity (above deck)

where:
capacity (below deck) = ((No. of bays x no. of tiers x no. of rows) x shape factor) (below deck)

It is obvious from the above that in order to determine the estimate of the capacity of the design proposal it is necessary to determine the number of bays, tiers and rows of containers required to be accommodated in the vessel. In order to do this it was proposed that a cubic numeral type of approach be adopted which relates the capacity of the basis vessel to that of the design proposal, as indicated below:

$$SF^3 = \frac{\text{required capacity of design}}{\text{capacity of basis}}$$

No. of bays (design) = no. of bays (basis) x SF
No. of tiers (design) = no. of tiers (basis) x SF
No. of rows (design) = no. of rows (basis) x SF

The above approach is adopted for both the below and above deck container arrangement. The dimensions of the design proposal are then produced by assuming that the dimensions of the cargo block are the same proportion of the overall vessel dimensions for both the basis and design proposals. This approach will obviously result in a geosim type of variation of the particulars of the basis vessel to produce the design proposal. There will often be the need to limit the extent of the expansion or contraction of the basis in any particular direction due to the application of limitation on the main dimensions as caused by navigational and other operational considerations. There will also often be the requirement to limit the vertical extent of the above deck container stowage due to stability, container securing and line of sight considerations. The method developed by the author does take into account these additional considerations and enables restrictions to be placed on the main dimensions and the maximum number of on-deck tiers together with restrictions on the

range of allowable values for the main dimensional ratios.

The approach outlined above enables an estimate of the main dimensions of the design proposal to be produced very quickly from the specification of the basic design requirements such as required container capacity, design speed, and the required dimensional constraints (if applicable). As can be appreciated, the approach does assume that the design vessel possesses a similar arrangement of hatchways and holds as the basis vessel, and that the position of the machinery is also the same on the design proposal as on the basis vessel. It is also assumed that the lengths of compartments such as the peaks and machinery space etc. are directly proportional to the overall length of the vessel. This can obviously lead to an incorrect estimate of the length of the vessel but considering that all that is required at this early stage is an estimate of the main dimensions, any errors introduced as a result of the assumptions made are of no great significance. Differences between the layout of the basis vessel and that of the design proposal are taken into account at a later stage in the design proposal development, in order to determine the actual required vessel dimensions.

The process for the generation of preliminary dimensions, as outlined above, is shown graphically in Figure 5.3.

2.2 Hullform Generation.

Having generated a first estimate of the main dimensions of the design proposal, the next logical step is to produce a hullform definition for the vessel. The obvious source of the hullform description for the design proposal is a basis form definition which can be modified to match the design proposal requirements in terms of main dimensions, fullness and distribution of fullness. Alternatively, a hullform description could be supplied by the system user in the form of either a set of tabular offsets or a sketch body plan. The containership knowledge base was developed to allow all three of the above methods of hull form definition to be utilised by using a series of procedures external to the main knowledge base. The complete hullform definition component of the knowledge base is shown in Figure 5.4.

2.2.1 Basis Vessel Hullform Input.

This method of hullform definition provides the most rapid means of developing a form which satisfies the requirements of the design proposal. The technique involves

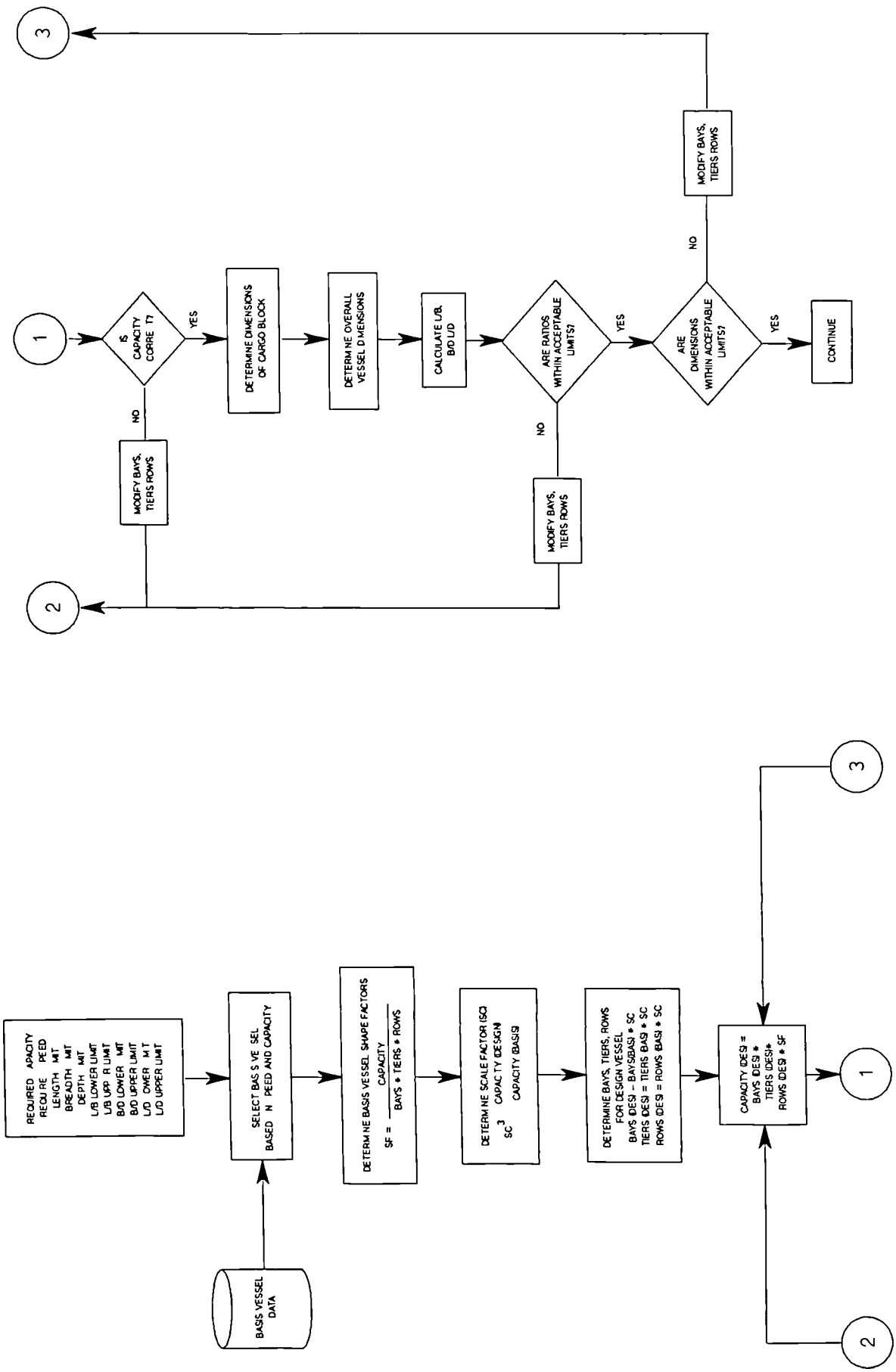


Figure 5.3 The process for determining preliminary dimensions of containership proposals.

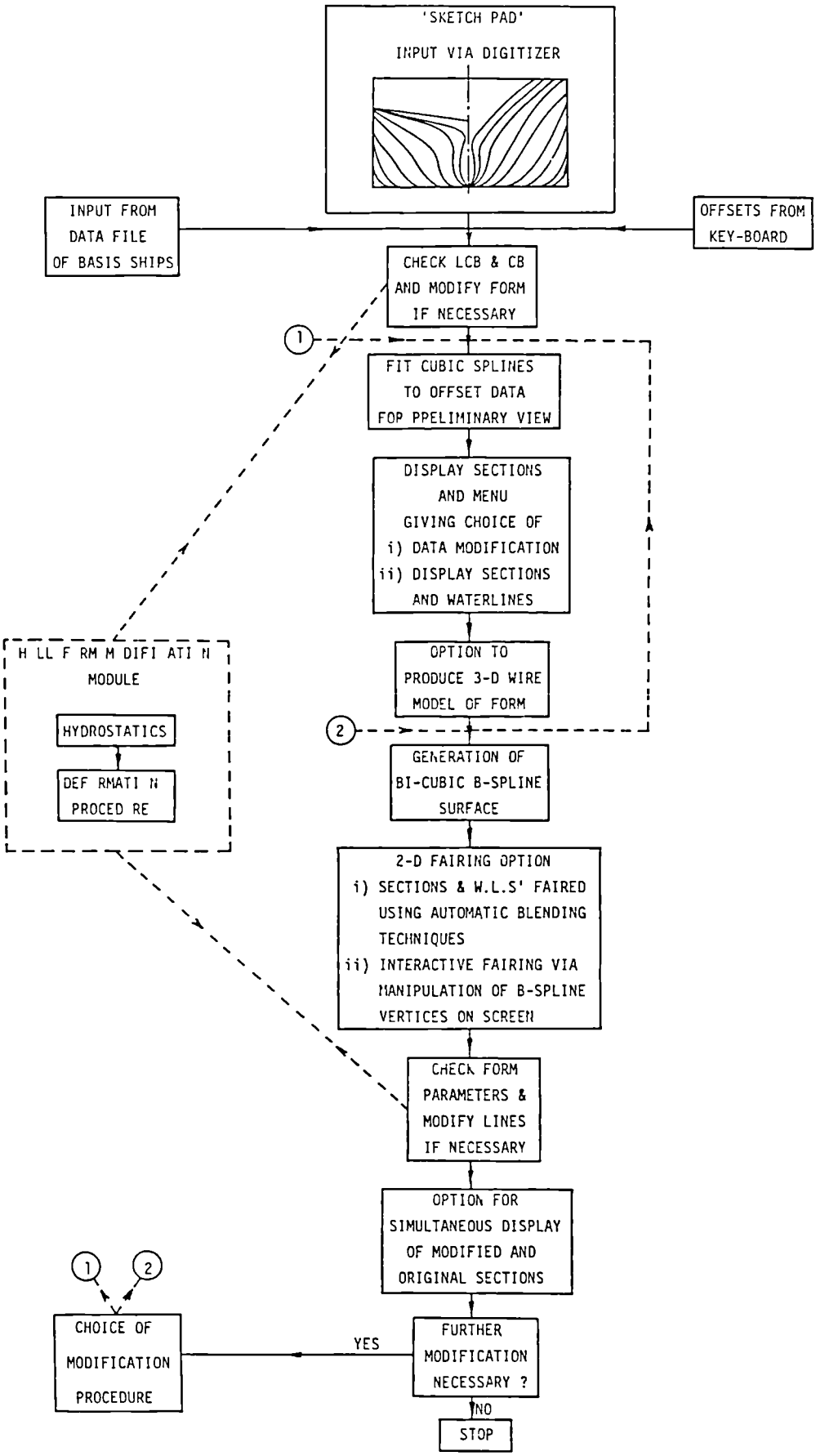


Figure 5.4 Overview of the hullform definition process.

the use of two procedures which permit the main dimensions of the form to be modified to suit the design proposal and the deformation of the hullform to provide the required block coefficient and position of longitudinal centroid. The first procedure involves a simple geosim variation of the hullform whereby the form particulars are scaled in the ratios of the basis to design main dimensions. The second process, deformation of the hullform, is based upon a technique developed by Lackenby [5.5] which permits changes to be made to the fullness of the hullform,the position and extent of parallel middle body and the location of the longitudinal centre of buoyancy.

The required block coefficient and position of longitudinal centroid are calculated within the knowledge base before being passed to the external hullform design procedures. The required value of block coefficient is determined using the expression proposed by Townsin [5.6] as shown below:

$$\text{Block coefficient} = 0.70 + 1/8 * \tan^{-1}25(0.23-Fn)$$

The position of the longitudinal centre of buoyancy is obtained by using the expression for centroid location according to the British Ship Research Association (BSRA) [5.7], as indicated below:

$$LCB = 20\,(Cb - 0.675)\ \%\ LBP \text{ from midships } (+\text{ve. fwd.})$$

2.2.2 User definition of hullform description.

As previously mentioned, there are two basic methods of user definition of a hullform description provided by the system; specification of a set of tabular offsets, and input from a sketch body plan.

2.2.2.1 Keyboard input.

The first of these options simply involves the system user typing hullform offsets into the system database via the computer keyboard. Although his method does provide a certain degree of flexibility in that hullform description obtained from a variety of sources can be entered into the database and used as the basis for design poposal development, it can be a very time consuming process and is prone to the introduction of errors into the associated data set.

2.2.2.2 Digitiser input.

The second of the user definition modes, input from sketch body sections, is by far the most flexible and easily used of the two available techniques. The procedure involves the system user digitising a set of sketch body sections into the system database from a digitising tablet attached to the computer system. The sketch can have been obtained from a variety of sources, such as the technical press, and can even be the users own interpretation of a hullform to meet the requirement of the design proposal. The hullform description, as defined by the sketch, can be to any scale and contain as few or as many sections as desired. There is also no real need for the sketch to be of a particular standard as the procedure developed allows smoothing of the input data to be carried out interactively. The whole procedure is based upon interactive graphics with the user being able to display the input sections, modify, delete or add the associated data points, generate additional sections by invoking a three-dimensional interpolation procedure and display waterlines at any specified height above the base of the vessel.

Smoothing of the input sectional point data can be carried out either on a manual basis, with the user manipulating the data points on the graphics screen via the digitiser mouse device, or under the control of the system using a technique based upon parabolic blending [5.8]. The procedure for using this automatic smoothing technique involves the system user indicating the data point, or points, to be smoothed by means of the mouse device. The system then proceeds to generate parabolic segments through the data points surrounding the erroneous points to produce a blended curve over the regions containing them. By assuming that the correct location for the erroneous point is on this blended curve, the procedure is able to determine the position for the point which would produce a smooth curve over the region under consideration. The parabolic blending procedure provides a very powerful means of smoothing point data, and has the effect of greatly speeding up the hullform smoothing process.

At this early stage of the hullform generation process, it was considered quite reasonable to adopt a cubic spline approach [5.9] to provide the means of visualisation of the input hullform data. The cubic spline is the mathematical equivalent of the flexible batten traditionally used to create representations of hullforms in ship design departments. Despite the disadvantages associated with the cubic spline representa-

tion, such as its tendency to oscillate between data points, it was adopted for inclusion in the system as it provides a very flexible and convenient method of modelling hullform data.

2.2.4 Hullform smoothing.

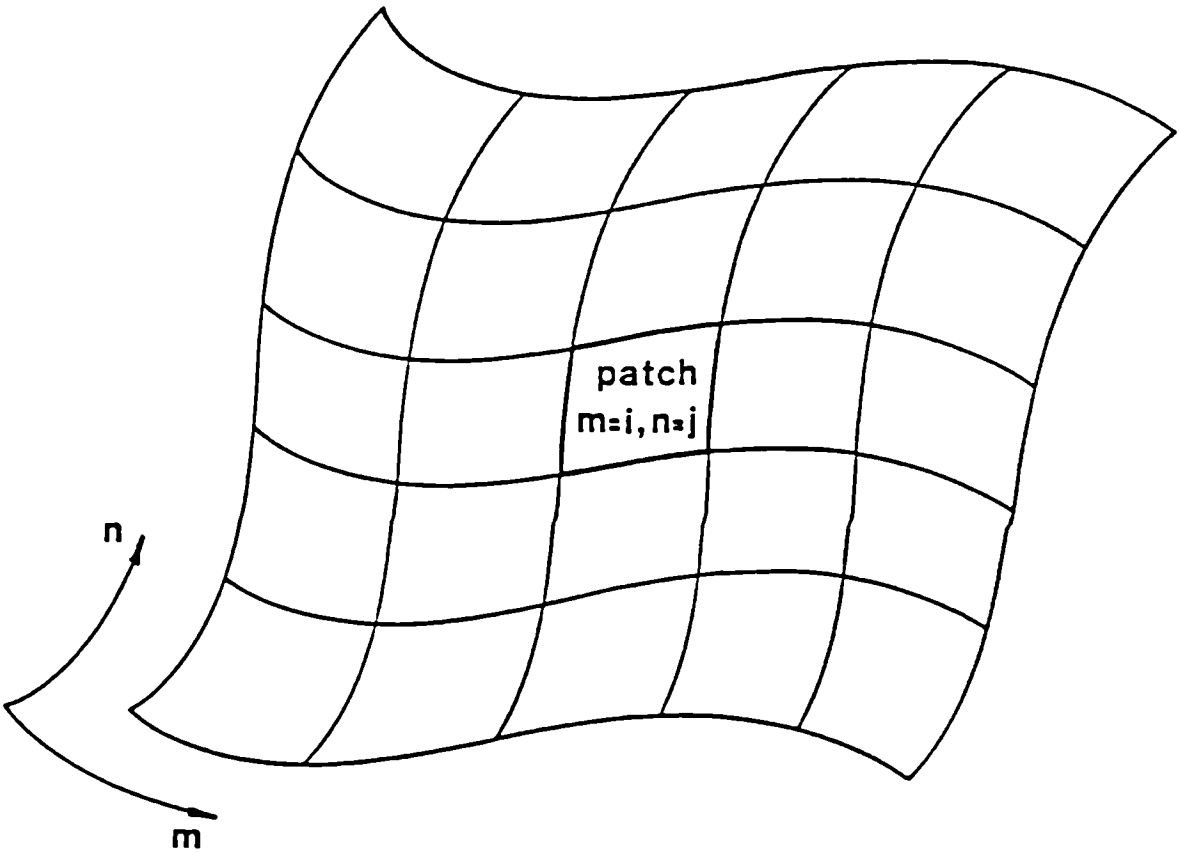
Regardless of which method of preliminary hullform data generation has been utilised, use can be made of the procedure to modify the hullform particulars (geosim and geometric variation) at any stage. In support of the hullform variation procedures, the author developed a hydrostatic particulars generation procedure to enable the geometric characteristics of the hullform to be determined at any specified vessel draft. The hydrostatic particulars routine, together with the geometric and geosim variation procedures, provides a means of monitoring the effect of any changes made to the hullform using the interactive graphics based modifications and smoothing procedures.

Once the initial hullform description data has been defined, the system provides the user with the means to further smooth the input data and also manipulate it so as to introduce any desired features into the form such as chines and knuckles. This procedure is also based on interactive graphics with the user selecting various menu options by means of the digitiser mouse device.

In order to allow the definition features such as chines and knuckles, it was considered necessary to adopt a three-dimensional surface representation of the hullform as opposed to the two dimensional spline models used for the initial data definition stage described previously. The technique selected to provide the basis for the three dimensional surface model was the bi-cubic B-spline surface as described in [5.10]. The adoption of a surface representation technique provides the system user with a very powerful tool for the interactive design of three dimensional forms without the need to explicitly maintain compatibility between the three orthogonal views.

The B-spline surface can be considered as comprising a mosaic of bi-cubic patches sewn together to form the complete surface, with each of the patches possessing first and second order continuity in each of its parametric directions. Control of the surface is achieved by means of the manipulation of a set of surface control vertices as illustrated in Figure 5.5, which provides the ability to exercise control over localised areas of the surface. This is due to the fact that a single bi-cubic B-spline surface

$$Q_{i,j} = \sum_{r=-2}^{1} \sum_{s=-2}^{1} b_s v \; V_{i+r,j+s} \; b_r u$$



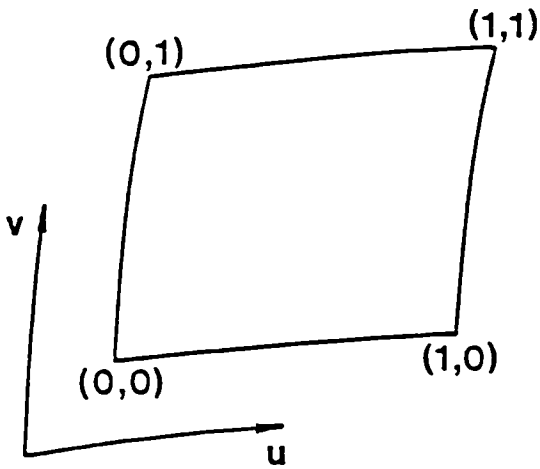


Figure 5.5 The B-spline surface formulation.

patch is influenced by 16 control vertices and is unaffected by all others. The converse is also true in that a single vertex has influence over only 16 surface patches with all others being unaffected, with the result that the movement of a given control vertex will effect only a small portion of the complete surface. This feature of the B-spline surface formulation was the main reason for this representation being selected in preference to others such as the Bezier surface [5.11], which do not permit localised surface control.

The main problem encountered when developing the B-spline surface theory for inclusion in the hullform generation procedure of the conceptual ship design system, was associated with the fact that the B-spline surface formulation does not immediately allow the user to specify points lying on the surface and then interpolate additional points using the surface formulation. This was considered a significant problem as the requirement of the approach was that the surface representation could be applied to the available hullform definition data, that is the pre-defined offset data. This therefore created the need to be able to develop the particular pattern of control vertices which would interpolate the required surface.

The B-spline surface is represented by the following formulation:

$$Qij(u,v) = \sum_{r=-2}^{1} \sum_{s=-2}^{1} b\,brs(u,v)\, Vi+r,j+s \quad \text{for } 0 <= u,v <= 1$$

where Qij(u,v) is a point on the ij th surface patch and is a weighted average of the 16 vertices Vi+r,j+s for r=-2,-1,0,1 and s=-2,-1,0,1.

In this expression, the set of bi-variate uniform basis functions is the tensor product of the set of univariate uniform basic functions:

$$b\,brs(u,v) = br(u)\, bs(v) \qquad \text{for } r=-2,-1,0,1 \;\; s=-2,-1,0,1.$$

The formulation for the patch Qij can be re-written:

$$Qij(u,v) = \sum_{r=-2}^{1} \sum_{s=-2}^{1} br(u)\, Vi+r,j+s\, bs(v) \qquad 0 < u,v <= 1$$

where:

$$[b_{-2}(u)\ b_{-1}(u)\ b_0(u)\ b_1(u)] = [u^3\ u^2\ u\ ^1]\ 1/6 \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 0 & 3 & 0 \\ 1 & 4 & 1 & 0 \end{bmatrix}$$

A technique was proposed by Barsky and Greenberg ([5.12], [5.13]) which works on the assumption that the available surface grid points are in fact the corner points of the B-spline surface patches and can therefore be used in the above formulation to solve for the associated pattern of control vertices. The technique as proposed by Barsky and Greenberg was implemented by Cheong [5.14] and was further developed by the author for incorporation in the hullform generation procedure described here.

As previously mentioned, the adoption of a three-dimensional surface representation of an input hullform description provides a very powerful tool for hullform manipulation and smoothing. Due to the fact that the vast majority of practising ship designers have no experience of manipulating hullform representations in three dimensions, a decision was made to take the surface representation and transform it into a more familiar two dimensional format of sections and waterlines for presentation to the system user. This move was purely intended to improve the user interface of the procedures and to put them into a more usable form, and in no way affected the three dimensional nature of the hullform model and the associated advantages of that kind of representation. As in the initial data definition procedures, the surface manipulation routines are controlled by means of user selectable menu options which provide for the movement and blending of the surface control vertices, and also for the generation of waterlines through the hullform.

The three dimensional nature of the hullform model removes the need for the system user to ensure compatibility between the various views of the hullform, when making any modifications to the form, as this is done automatically. The use of the bi-cubic B-spline surface representation also means that localised features can be introduced into the form by means of the manipulation of the surface control vertices. For example, the bi-cubic nature of the surface means that three control vertices coincident will result in the appearance of a discontinuity in the surface in the region of the vertices. The technique can be used with considerable effect for the introduction of

features such as chines and knuckles into hullforms, as illustrated in Figure 5.6. As previously mentioned, the manipulation of individual vertices can result in errors such as flat spots, bumps and hollows, being removed from the hullform, this being achieved either on a manual basis, using the digitiser mouse, or by parabolic blending of the vertices.

The procedures described above provide the conceptual ship design system with a powerful hullform generation capability which makes very effective use of interactive graphics to give a highly user-friendly interface to the system user. The quality of the hullform representations which can be derived from the system is illustrated in Figure 5.7, which shows three views of a hullform for a containership.

As previously stated, this aspect of the design system was considered to be ship-type independent and as such was developed so that it could be applied to the development of hullforms for vessels of any type. An example of the application of the procedures to the development of the hullform of a medium-size Ro-Ro vessel can be found in [5.15] which is reproduced in Appendix I. This reference also provides further detail of the structure and content of the hullform generation procedures, with additional information being given in [5.16].

2.3 Generation of the outline general arrangement.

Once an estimate of the preliminary dimensions of the design proposal has been obtained, and a suitable hullform generated using the procedures described above, the next stage in the development of a design proposal is the generation of an outline general arrangement for the vessel.

The design of the general arrangement of any vessel is perhaps the most important aspect of the whole design process, as decisions made at this stage have a far reaching effect on the final outcome of the design investigation. The general arrangement of a vessel has a significant effect on its physical behaviour (in terms of trim, stability and strength), its operational characteristics, such as cargo handling, its overall economic performance, and finally, the relative ease with which it can be produced. The definition of a general arrangement therefore assumes a central position in the whole design process and forms the essential basis for subsequent stages of the design cycle.

In the context of the ship design system, the design of the general arrangement of

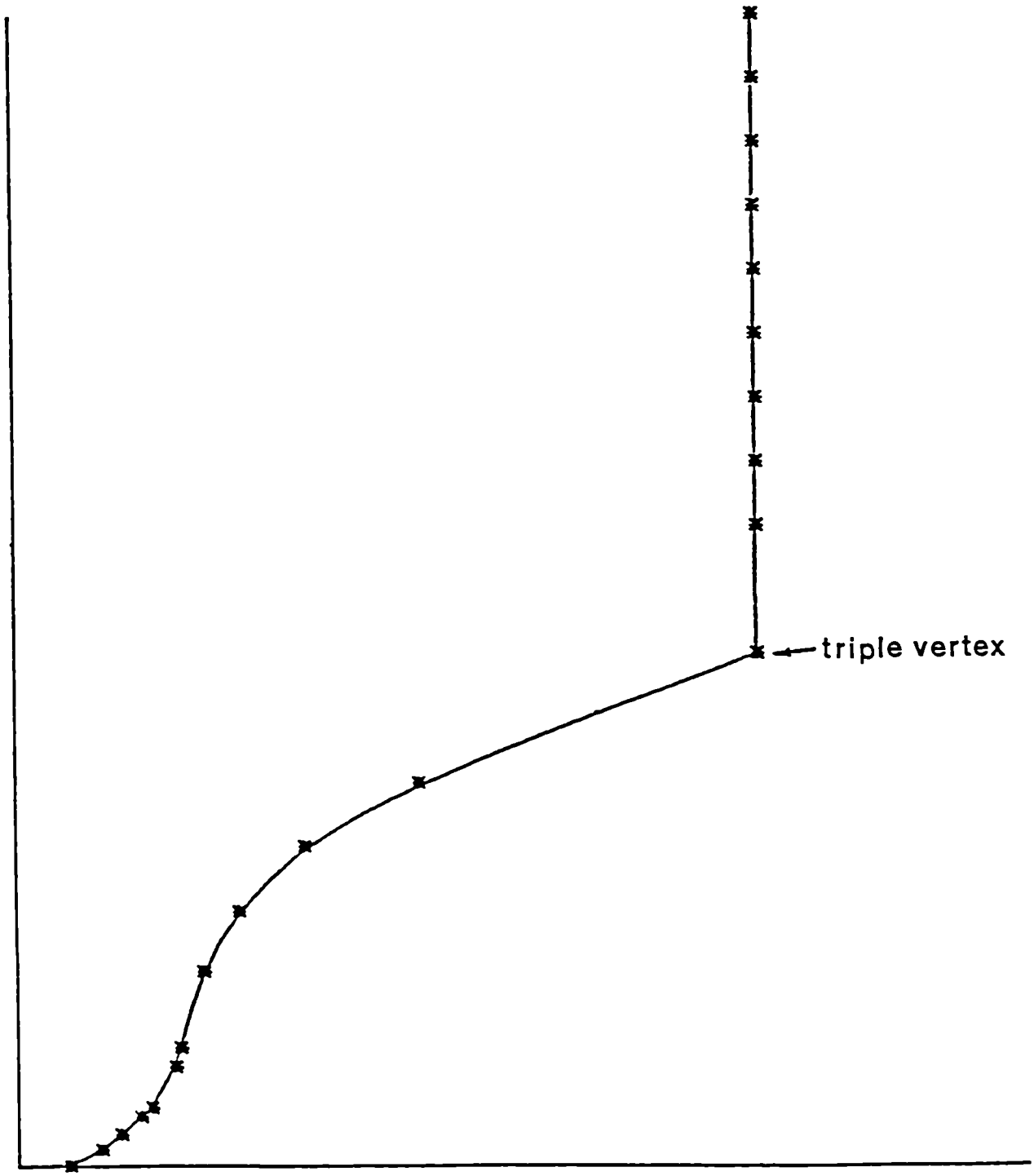


Figure 5.6 The definition of a localised hullform feature.

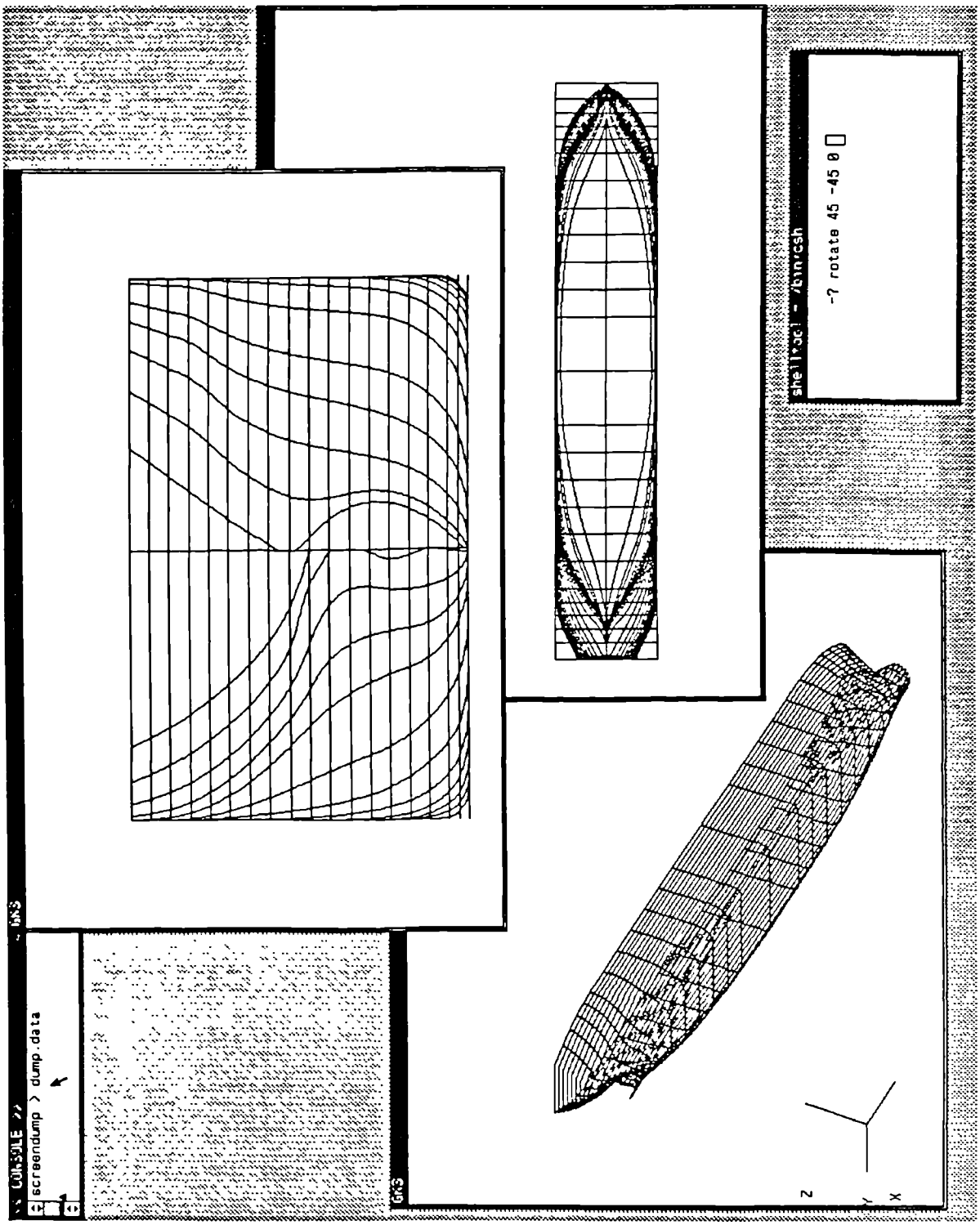


Figure 5.7 Graphical representations of a containership hullform.

a design proposal is achieved by means of a combination of heuristic reasoning and the use of a suite of external analysis procedures. Such a combination permits arrangements to be developed based upon the knowledge and expertise extracted during the knowledge elicitation sessions discussed previously, and then analysed to ensure their feasibility and compliance with the requirements of the design specification. These analysis procedures cover such areas as powering, engine selection, hydrostatic particulars determination, stability characteristics, freeboard investigation, container capacity determination, tank arrangement and tank capacities calculation.

2.3.1 Location of the main hold bulkheads.

The first stage in the generation of a preliminary general arrangement is the positioning of the main transverse sub-division bulkheads to form the hold, engine room, and peak boundaries. The method utilised within the system to determine the required number of bulkheads is based upon the requirements of Lloyds Register [5.17] which relates the required number of bulkheads to the proposed length of the vessel and the position of the machinery space. These requirements are summarised in Table 5.1.

As can be seen from the Classification Society requirements, vessels over a length of 190 metres are not considered, with the result that the number of bulkheads to be incorporated in such vessels has to be determined by consideration of the flooding characteristics of the proposal. The method adopted for use in the system for vessels with lengths beyond the 190 metres threshold is based upon [5.18], and uses approximate floodable length curves to determine the acceptability of a proposed arrangement of transverse bulkheads. The method works by using standard floodable length curves which are corrected for variations from the assumed standard of block coefficient, sheer line etc., by means of coefficients relating to the actual parameters of the design proposal.

Although only an approximate method for the generation of floodable length curves, the technique utilised in the system does provide an extremely fast and convenient method of assessing the suitability of a proposed arrangement with respect to transverse sub-division standards, and is in fact a method currently used by practising ship designers.

If it is assumed that the required number of transverse bulkheads has been determined, then the next step in the development of a general arrangement is to obtain the number of holds to be incorporated in the vessel. Within the design system it is assumed that the number of holds is obviously related to the number of bulkheads as illustrated in Figure 5.8. As can be seen from the diagram, the number of holds in a vessel is equal to the number of bulkheads less two, regardless of the position of the engine room.

The actual positions of the main bulkheads is dependent upon a number of factors. As previously discussed (Chapter 4), the length of a containership, and hence the disposition of the main transverse bulkheads, is a primarily a function of the size of the container units to be carried and the number of individual container bays along the length of the vessel. Allowance must also be made for structural and stowage clearances between the individual container bays and adjacent hatches and holds. In order to determine the overall length of a particular cargo hold it is therefore necessary to determine the number of container bays to be accommodated in the hold. This is achieved by first of all attempting to distribute the total number of bays evenly between the number of holds, and then assigning additional bays to some holds until the correct number of bays has been accommodated. For example, the number of bays per hold can be determined from:

number of bays per hold = total number of bays / number of holds

where *number of bays per hold* is rounded down to the nearest integer.

Obviously the above action could result in the number of bays initially accommodated being less than the number required. To overcome this, additional bays are assigned to selected holds, as mentioned above, until the required number has been reached. The assignment of these additional bays to individual holds is on the basis of starting with the holds in the fullest region of the vessel (around the midships region) and then working forward and then aft, adding bays to the holds until all of the required bays have been accommodated. It should also be appreciated that the number of hatches required to accommodate the specified container bays must also be considered at this stage. The number of container bays to be located in each hatchway will be dependent upon the size of the container bay. For example, it is assumed that two standard 20 foot container bays can be accommodated in a single hatch, with this

Length, L, in metres	Total number of bulkheads	
	Machinery amidships	Machinery aft*
≤ 65	4	3
> 65 ≤ 85	4	4
> 85 ≤ 90	5	5
> 90 ≤ 105	5	5
> 105 ≤ 115	6	5
> 115 ≤ 125	6	6
> 125 ≤ 145	7	6
> 145 ≤ 165	8	7
> 165 ≤ 190	9	8
> 190	To be considered individually	

*With after peak bulkhead forming after boundary of machinery space

Table 5.1 Classification Society requirements for transverse bulkheads.

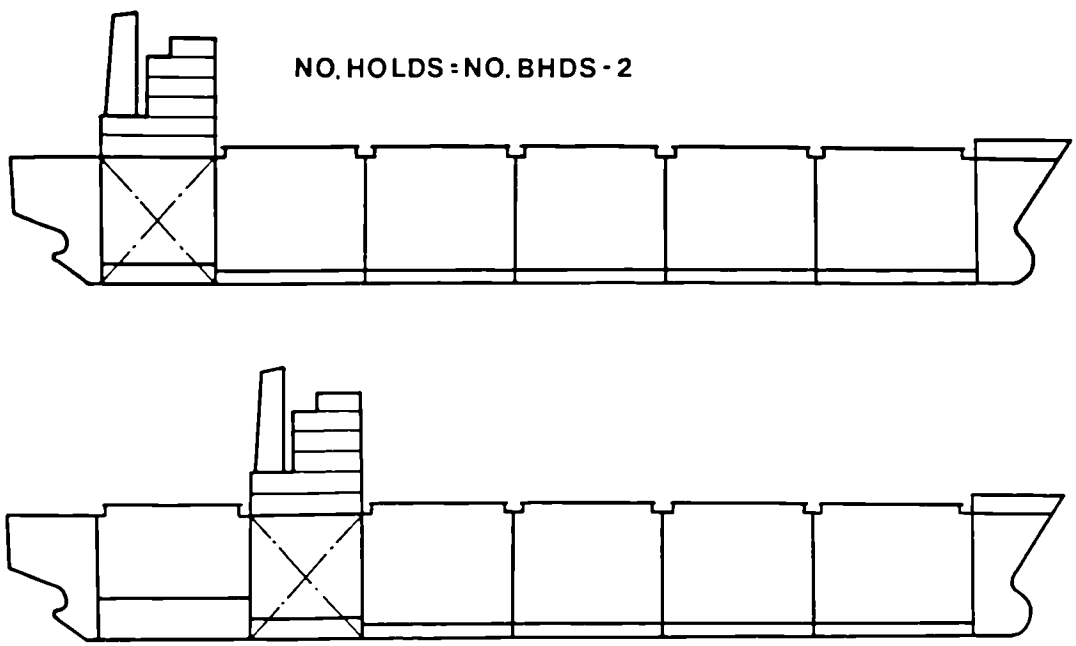


Figure 5.8 Illustration of the relationship between number of bulkheads and number of holds.

being reduced to one for any other size of unit. This assumption will determine the number of hatchways to be found in each of the holds in the vessel. The occasion could arise, due to the total number of bays being odd, whereby one of the hatches in the vessel is required to accommodate a single container bay even when the unit is of the standard 20 foot type. Under these circumstances the single bay hatch would be located at the extreme forward end of the vessel in hold number one.

The ability of the containership to possess muliple hatches along the length of a hold is due to the incorporation of non-watertight transverse web frame structures between the individual hatches, as discussed in the previous Chapter of this thesis, to transmit the loadings from the hatch supporting structures.

The assumptions outlined above can result in various arrangements of holds and hatches. As can be seen from Figure 5.9 which shows a typical profile of a containership, the lengths of the individual holds is a function of the clearances between the individual containers, together with the between-hatch gaps. The gaps between the individual containers is dependent upon the type of container stowage equipment to be utilised on the vessel, as this will determine the clearances required for the hold cell-guides etc. It is considered reasonable to assume that a gap of 76 mm. is sufficient between adjacent containers bays as this is the clearance used by most below-deck cell guide systems, and also permits a forty foot container to be accommodated in two twenty foot cells. In addition to the between container clearances, there is also a need for clearances between the hatch end structure and the end of the adjacent container, this again being as a result of the need to accommodate the container securing system. It is therefore assumed that a gap of 100 mm at the ends of each hatch is sufficient to ensure adequate clearance for the installation of the selected cell guide system. Figure 5.10 shows a typical hatch arrangement with the associated container clearances. It should be noted that as the length of a particular hatch will undoubtedly be a multiple of the frame spacing of the vessel, the length of the hatch obtained from consideration of the container dimensions and the required gaps will be a minimum figure and the actual hatch length will normally be greater than this when frame spacing is taken into account.

The required gap between adjacent hatches is dependent upon a number of factors such as the type of cargo handling gear fitted (if applicable) and the frame spacing of the vessel. It is assumed that the gap between adjacent hatches in the same hold, as

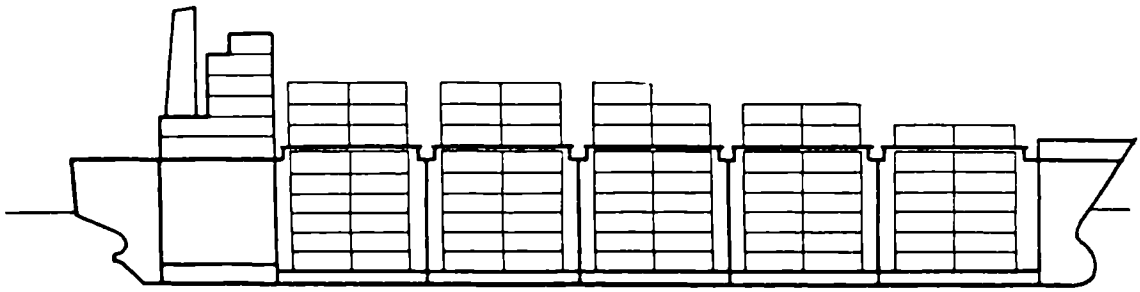


Figure 5.9 Profile showing a typical hold and hatch arrangement.

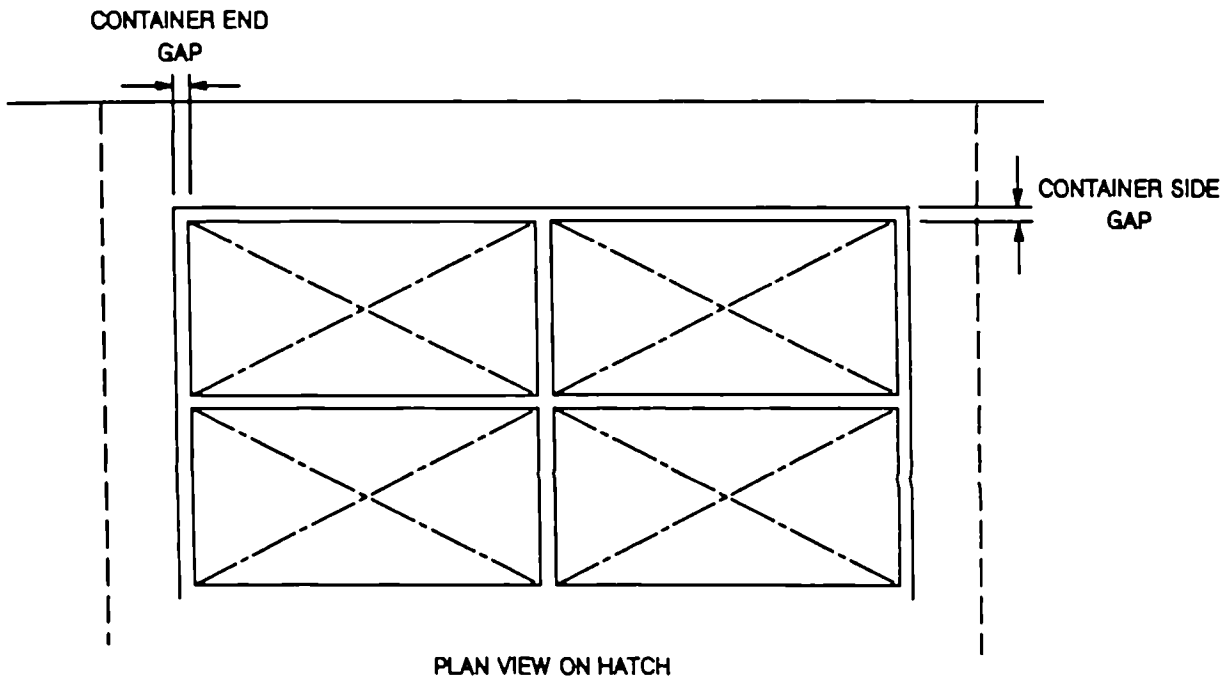


Figure 5.10 Illustration of the clearances required to accommodate a cell-guide system.

shown in Figure 5.11, is equal to a two frame spaces as this is sufficient to allow the incorporation of a transverse web frame structure if required. The gap between adjacent hatches in neighbouring holds is dependent upon whether cargo handling equipment is fitted or not, and the type of gear if applicable. If no cargo handling equipment is fitted then the between-hatch gap is assumed to be equal to two frame spacings, as shown in Figure 5.12, with the relevant transverse bulkhead occupying this gap. This is also the case if travelling gantry cranes are fitted to the vessel as the use of this particular type of equipment does not incur an increase in the size of the between-hatch gaps. The installation of deck cranes of the pedestal type does involve an increase in the between-hatch clearance due to the need to accommodate the crane pedestal and the associated supporting structure. Obviously the size of the gap will be largely dependent upon the size of the crane pedestal and the clearance between the pedestal and the adjacent hatches. Within the ship design system it is assumed that the diameter of any crane pedestal is equal to four frame spaces and that a gap of one frame space is required between a pedestal and the adjacent hatches, as shown in Figure 5.13. It is further assumed that the number of deck cranes is equal to the number of holds in the case of pedestal cranes, due to the need for the transverse bulkheads to support the loads imparted by the cranes, and that there is only a single crane if gantry based equipment is specified.

2.3.2 Determination of actual required depth of the vessel.

As a next step, it is necessary to determine the required depth of the vessel in order to accommodate the below-deck tiers of containers. This is a fairly straight-forward procedure as the depth of a containership is directly dependent upon the size of the container unit to be carried. In determining the depth of a containership it should be noted, however, that the heights of individual containers can vary quite considerably with deviations from the standard 8' 6" high container being commonplace. In fact, the available container heights range from 8' to 9' 6" with the addition of half-height containers for the carriage of particularly dense cargoes. It is quite obvious that if a vessel is to be designed with the capability of accommodating containers of different heights, then the depth of the vessel must be determined with reference to the greatest container height which is intended to be carried.

Having decided upon the average height of container which is to be carried, the depth

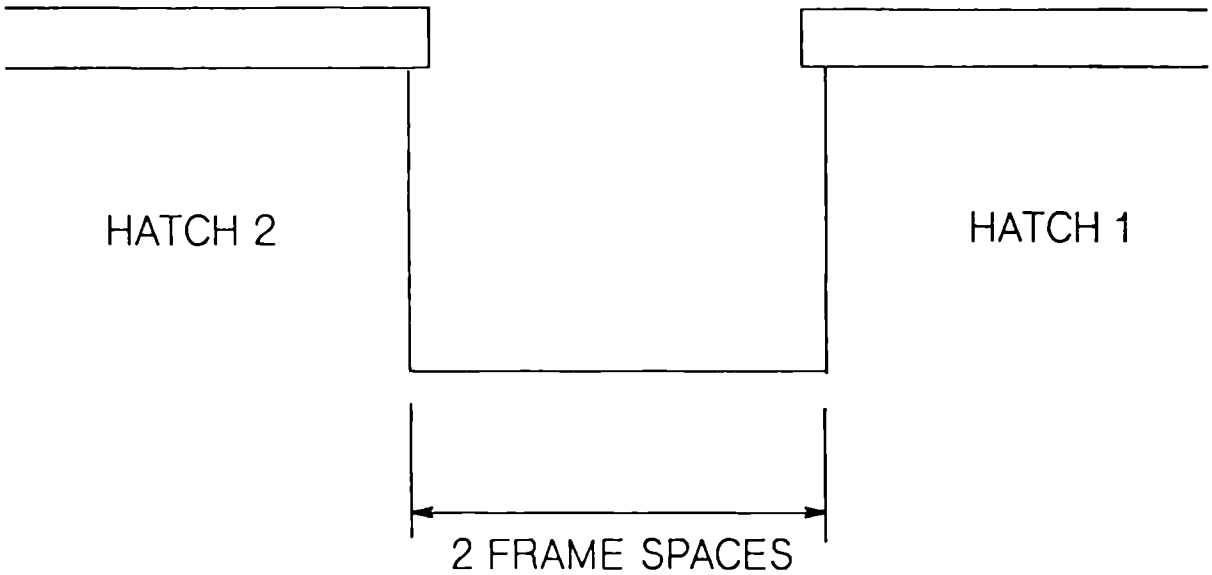


Figure 5.11 Illustration of the clearances between adjacent hatches in the same hold.

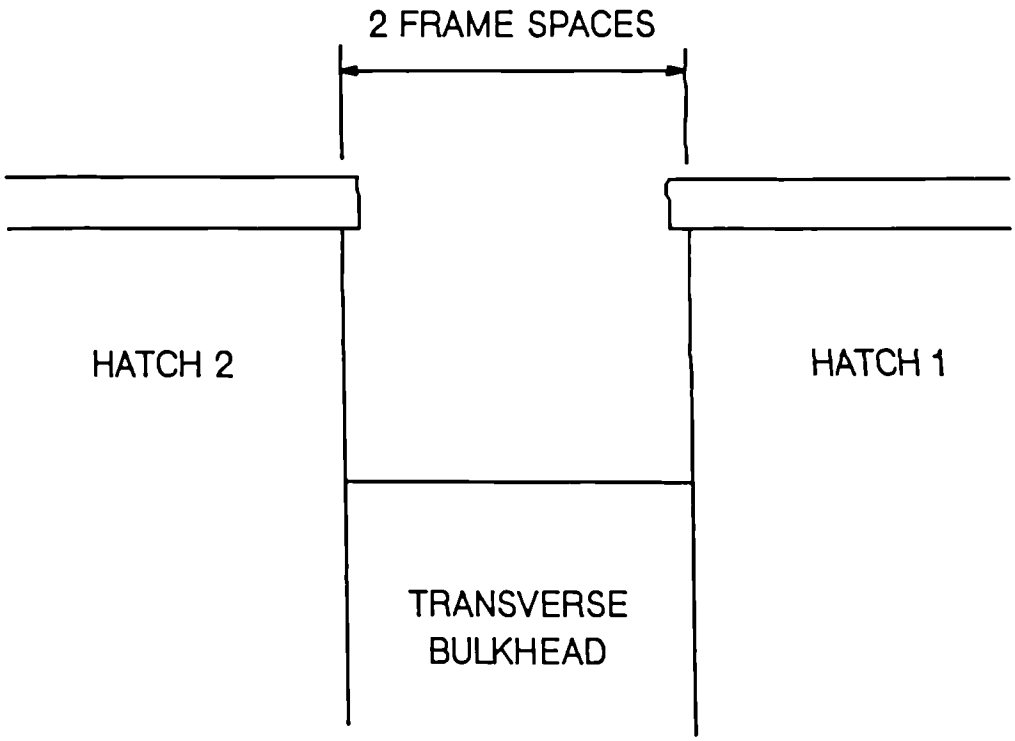


Figure 5.12 Illustration of the clearances between hatches in adjacent holds - no pedestal cranes.

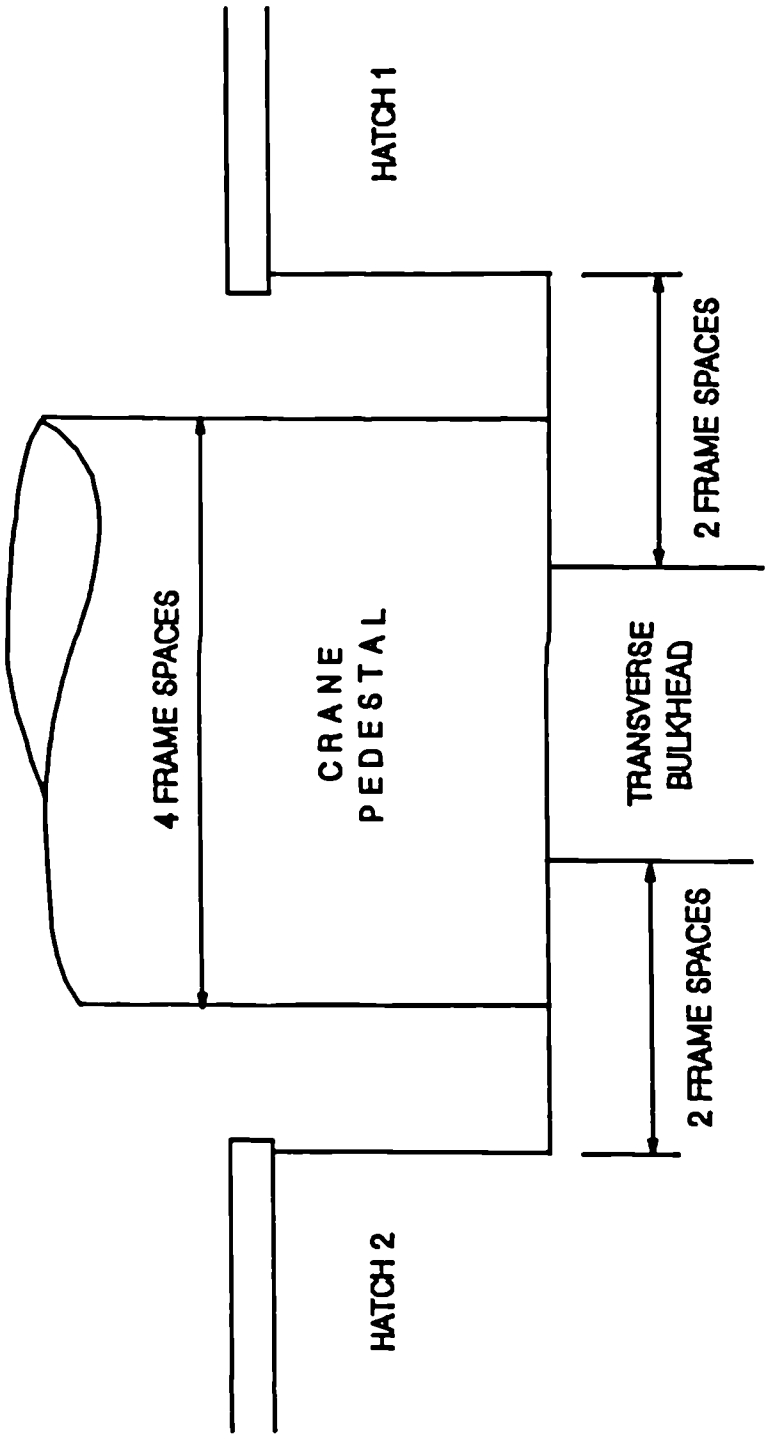


Figure 5.13 Illustration of the clearances between hatches in adjacent holds - pedestal cranes.

of the vessel can be determined by consideration of the number of tiers of containers to be accommodated, as shown in Figure 5.14. As can be seen from the diagram, in order to calculate the depth of the vessel it is necessary to estimate the height of the tank top in the cargo region. The procedure used in the design system for the calculation of the tank top height is based upon the expression for centre girder height defined by the Classification Society [5.17], as shown below:

$$G = 28B + 205\sqrt{T}$$

where :

G is the minimum height of the double bottom centre girder in mm,
T is the draft of the vessel in metres.
B is the breadth of the vessel in metres.

The height of the hatch coaming is assumed in the system to be equal to 1.40 metres, a figure which corresponds to that used on many containership designs, while the under-hatch clearance has been assumed to be equal to 100 mm.; again a figure obtained from existing designs.

As the draft of the vessel is not known at this early stage, the expression for the vessel depth has to be re-arranged to allow the draft to be expressed as a function of depth. If it is assumed, therefore, that the draft of the vessel is equal to 70% of the preliminary depth as determined previously, the following expression can be obtained:

$$D = GM + UHC + NOT * (CH + VG) - CHT$$

where :

D is the depth of the vessel in metres,
GM is the height of the tank top above base in metres,
UHC is the under hatch cover clearance in metres,
NOT is the number of tiers of containers in the holds,
CH is the container height in metres,
VG is the vertical gap between containers in metres,
CHT is the height of the hatch coaming in metres.

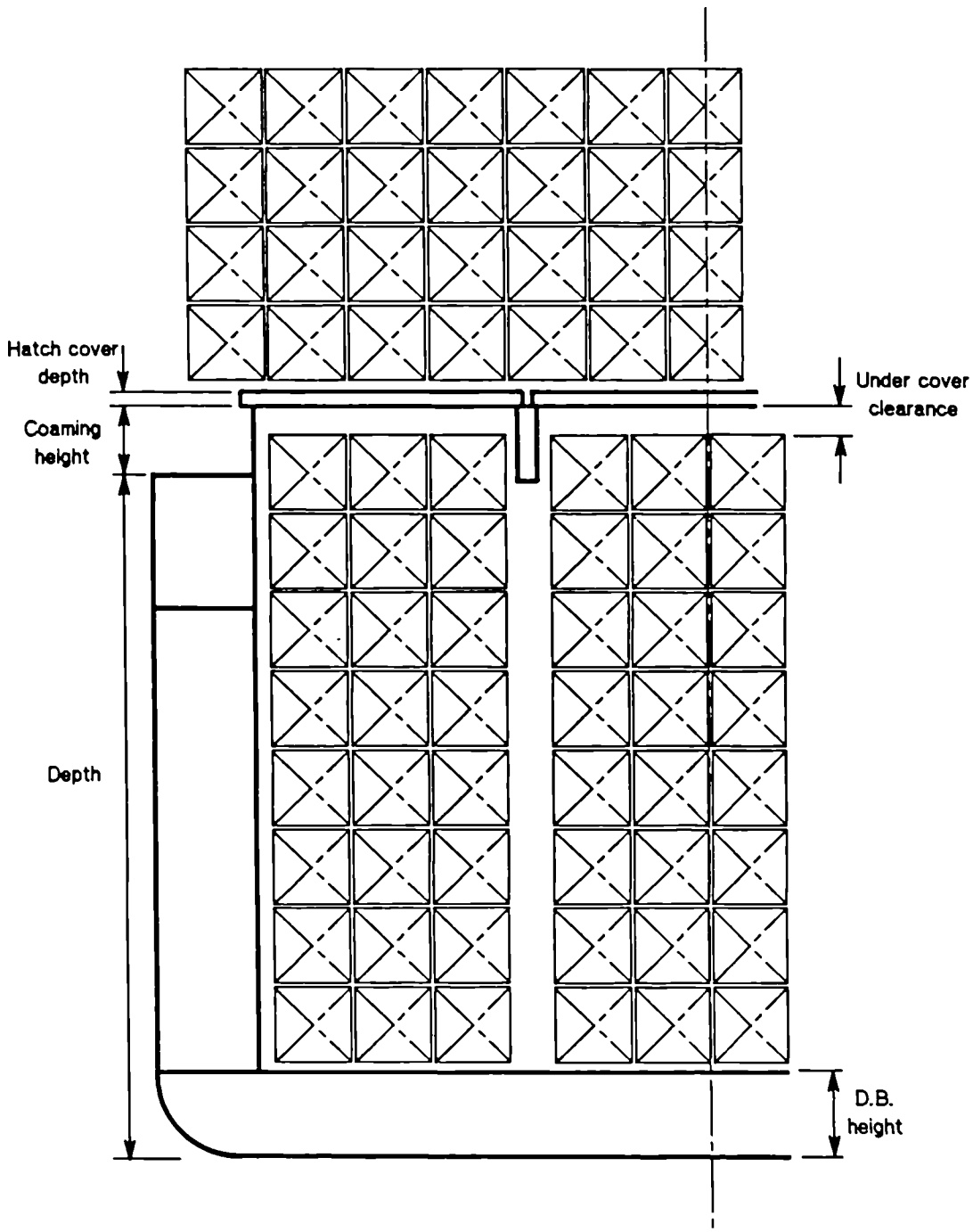


Figure 5.14 The factors which determine the depth of a containership.

With each of the above parameters being known the required depth of the vessel can be determined quite easily.

2.3.2.1 Freeboard calculation.

The determination of the vessel depth permits the calculation of the required freeboard of the vessel to be performed. In order to carry out this calculation the system utilises a procedure developed by the author based upon the Load Line Regulations [5.19]. This freeboard calculation routine works by obtaining the tabular freeboard at the relevant ship length from a datafile of tabular freeboard values, and then applying the corrections for variations in block coefficient, depth, sheerline, superstructure etc., from the assumed standard values. Some of these items can be obtained directly from the hullform description data, but others require assumptions to be made by the system. For example, it is assumed that the freeboard deck is equivalent to the second deck which is itself located at a distance of 3.00 metres below the upper deck (this height being selected so that the 'tween deck space can be used as a means of access along the length of the vessel). This arrangement results in the creation of a superstructure which runs the full length of the vessel, a fact which greatly simplifies the freeboard calculation. The final item which has to determined, the sheer profile, is again simplified by the assumption that the final freeboard deck is the second deck, as it considered reasonable to assume that this deck will have zero sheer in both the forward and aft directions.

2.3.3 Location of the peak bulkheads.

Consideration of the arrangement of holds and hatches, together with the associated gaps and clearances, and the dimensions of the container units themselves, permits the layout of the complete cargo section of the vessel to be determined. In order to complete the arrangement and determine the location of the cargo portion along the length of the vessel, it is necessary to consider the location and extent of the machinery space and the lengths of the aft and fore peak regions.

The extent of the fore peak region, as determined by the location of the collision bulkhead, is quite easily determined according to Classification Society rules [5.17]. These rules relate the position of the collision bulkhead to a range of acceptable locations relative to the forward perpendicular. The position of the aft and forward

limits for the bulkhead location is dependent upon the length of the vessel and the extent of the protrusion of the bulbous bow, if applicable, as shown in Figure 5.15. Once the forward and after limits of the bulkhead location have been determined the choice of the actual position of the bulkhead is fairly arbitrary although it obviously has to coincide with a frame. In the context of the ship design system, the location of the collision bulkhead is selected as being half way between the two limits as defined, with an adjustment to its position being made to ensure that it lies on the nearest frame.

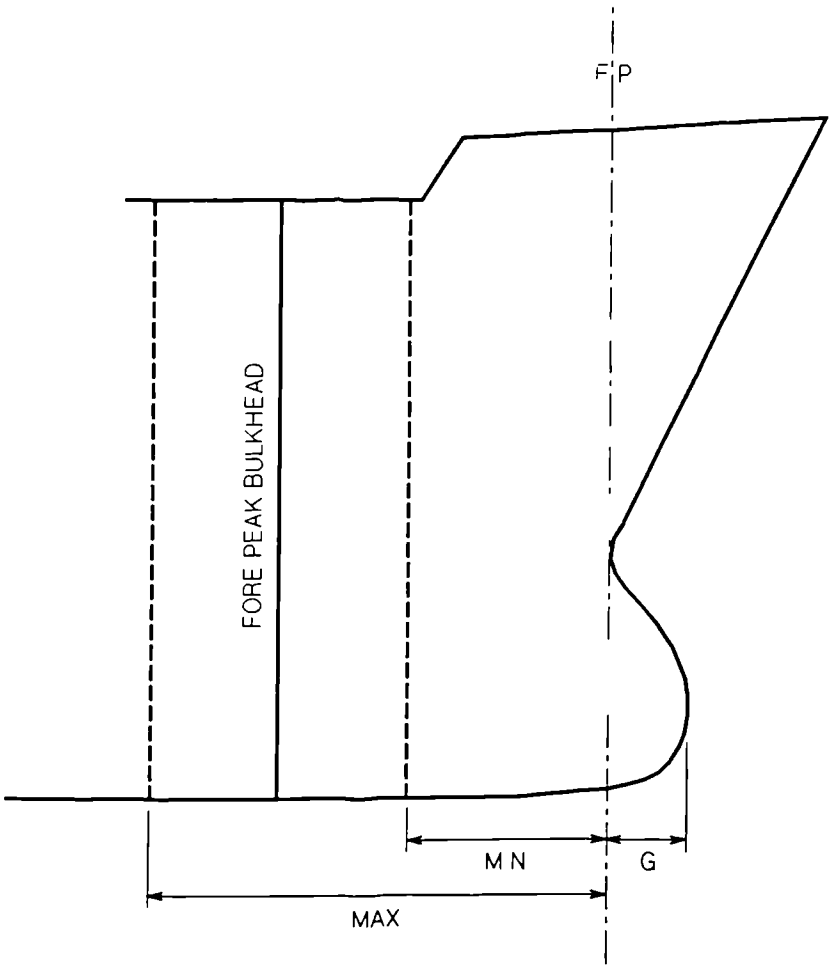
The situation concerning the location of the aft peak bulkhead is less well defined with its position being largely determined from consideration of the shaping of the aft end of the vessel and the need to accommodate the propeller shaft and the associated fittings etc. (on a single screw vessel). Obviously, on vessels where the machinery is positioned in the full aft position, the aft peak bulkhead will also form the aft engine room boundary. In the context of the design system, it was arbitrarily decided that the distance from the aft perpendicular to the aft peak bulkhead would be assumed initially to be 5% of the length of the vessel, with this being subject to change to suit the requirements of the engine room position.

2.3.4 Determination of the machinery space size and location.

Having decided on the lengths of the peaks of the vessel and knowing the overall length of the cargo region, it only remains to determine the position and extent of the machinery space in order to complete the profile arrangement of the vessel. The size of an engine room is obviously dependent upon the space required for the installation, operation and servicing of the equipment to be accommodated. Without doubt, the main propulsion engine is the largest single item of machinery to be accommodated in the machinery space and will have the greatest effect on its size and position. Therefore, when attempting to determine the particulars of the machinery space, the characteristics of engine to be installed in the vessel must be determined as a first step.

2.3.4.1 Selection of the main engine.

In order to determine the type of main engine to be installed in the design proposal, it is necessary to obtain an estimate of the power and engine speed required to achieve



L_1 = Length Between Perps.

Arrangement	Length L_L, in metres	Distance of collision bulkhead aft of fore end of L_L, in metres	
		Minimum	Maximum
(a)	≤ 200	$0{,}05L_L$	$0{,}08L_L$
	> 200	10	$0{,}08L_L$
(b)	≤ 200	$0{,}05L_L - f_1$	$0{,}08L_L - f_1$
	> 200	$10 - f_2$	$0{,}08L_L - f_2$
Symbols and definitions			

$f_1 = \frac{G}{2}$ or $0{,}015L_L$, whichever is the lesser

$f_2 = \frac{G}{2}$ or 3 m, whichever is the lesser

G = projection of bulbous bow forward of fore end of L_L, in metres

Figure 5.15 The position of the collision bulkhead.

the desired design speed. In this respect, a decision was made to utilise a powering procedure developed by a third party to derive an estimate of the required installed power and engine revolutions per minute. The procedure developed by Marine Design Consultants Limited, based upon a statistical analysis of powering data carried out by Holtrop and Mennen ([5.20], [5.21], [5.22]), was further developed by the author for inclusion in the ship design system. As previously mentioned, the procedure derives an estimate of powering requirements by considering the components of resistance by means of a series of expressions obtained from a statistical analysis of resistance data. The various factors affecting the propulsion characteristics are also considered in a similar fashion using regression equations derived from existing data. The procedure, as developed by Marine Design Consultants Limited, also includes an element for the optimisation of the required propeller and the associated propeller revolutions per minute. As it is assumed that the propulsion device will be a direct drive slow speed diesel engine, the determination of the optimum propeller speed implicitly specifies the required engine speed. In order for the powering procedure to be able to produce an estimate of the power requirement for a given ship speed, a number of data items have to be supplied covering areas such as the draft and other main dimensions of the vessel, the block coefficient at this draft, the longitudinal centre of buoyancy location, the number of screws, and the propeller diameter. Most of the above items relate simply to the hullform description, such as the block coefficient and the position of the centroid, and can easily be determined from the hullform data. As at this stage the actual required design draft of the vessel is not known, the draft of the vessel is initially assumed to be some proportion of the depth of the vessel. The actual vessel draft will be dependent on the lightmass of the vessel which is in turn dependent upon the machinery mass. The machinery mass is itself a function of the required power which at this stage has still to be determined. By assuming that the draft is a proportion of the vessel depth, an initial estimate of the required power can be made using the powering procedure. From this initial estimate an approximation to the mass of the machinery is obtained using the empirical expression proposed by Bentley [5.4], as shown below:

$$\text{Machinery mass} = 0.069545 * Pd + 60 \quad \text{(tonnes)}$$

where Pd is delivered power in kW.

By using the following expressions, also proposed by Bentley, for steelmass and outfit

mass, an approximation to the complete lightmass can be derived:

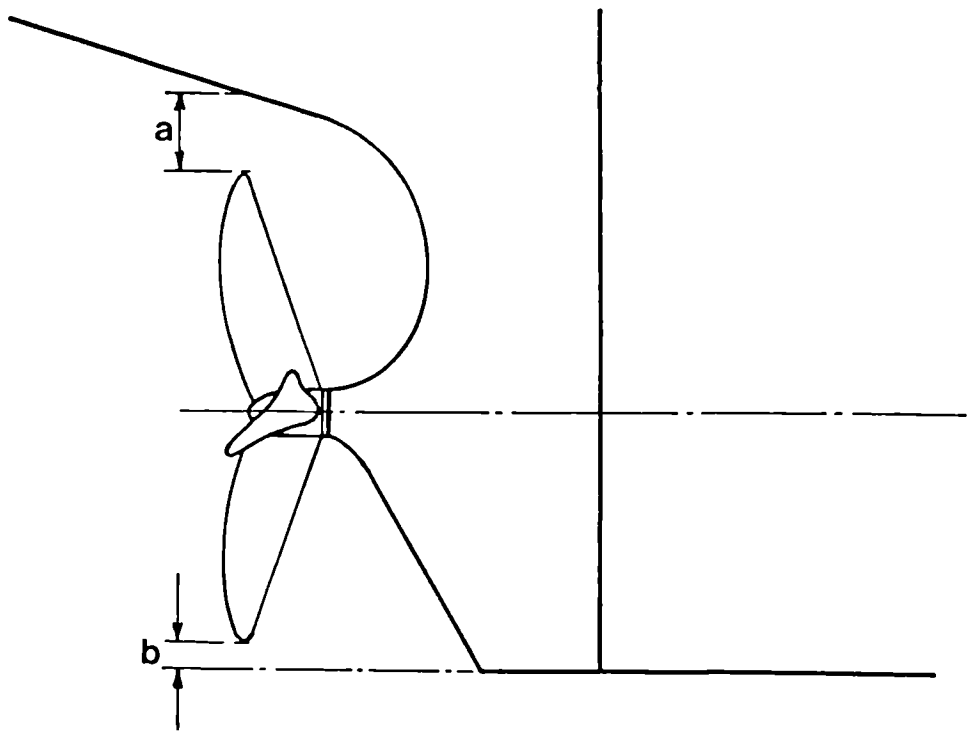
$$\text{Steelmass} = 0.078098 * L * B * D + 400 \quad \text{(tonnes)}$$
$$\text{Outfit mass} = 0.35142 * L * B + 95 \quad \text{(tonnes)}$$

It should, however, be appreciated that the above expressions can be modified or replaced as desired due to the design system being based upon an expert system approach and the flexible nature of such systems.

In order to obtain an estimate of the vessel displacement from which the revised draft can be obtained, it is necessary to first determine the other component of displacement, the deadweight of the vessel. Obviously the deadweight of the design proposal is dependent upon a number of factors which cannot easily be identified at this early stage, such as fuel capacity, fresh water capacity, diesel oil requirement and so on. It is therefore assumed that the total deadweight can be related to the largest single component of deadweight, the cargo mass, by means of a factor which allows for the other deadweight items. The mass of cargo can quite easily be determined by assuming an average mass to be carried in each container on the vessel and multiplying this by the total number of containers to be carried. This total cargo mass can then be multiplied by the assumed factor to produce an estimate of the total deadweight carried by the vessel. Once this has been done, an approximation to the displacement of the vessel can be calculated. Using this value of displacement together with the other main dimensions and the block coefficients, as determined previously, the revised vessel draft can easily be calculated.

Another data item required by the powering procedure is the diameter of the propeller to be installed on the vessel. This is determined by examination of the shaping of the aft end of the vessel to assess the maximum size of propeller which can be accommodated in the aperture without violating the Classification Society requirements [5.17] as shown in Figure 5.16.

The procedure as described above will undoubtedly produce a revised vessel draft which is considerably different from this initial estimate, therefore suggesting that an iterative approach be adopted to obtain the final estimate of the vessel design draft. In fact the ship design system does adopt this iterative approach with the above process being repeated until the value for the design draft converges to a single point. The iterative process described above is shown graphically in Figure 5.17. Once the



ASSUMING A 4-BLADED PROPELLER:

$a = K * d \qquad b = 0.03 * d$

$d = F - a - b$

$d = F - a - 0.03 * d$

$1.03\ d = F - a$

$d = (F - a) / 1.03$

$a = K * (F - a) / 1.03$

$1.03\ a = K * F - K * a$

$a = K * F / (1.03 + K)$

$d = (F - K * F / (1.03 + K)) / 1.03$

where :

$K = (0.1 + L/3050) * (3.48 * Cb * P/L^2 + 0.3)$

L = Length between perps. Cb = Block coefficient

P = Shaft power (Assume $P/L^2 = 1$ ... conservative)

d = Propeller diameter F = Size of aperture

Figure 5.16 Locating the propeller in the aperture.

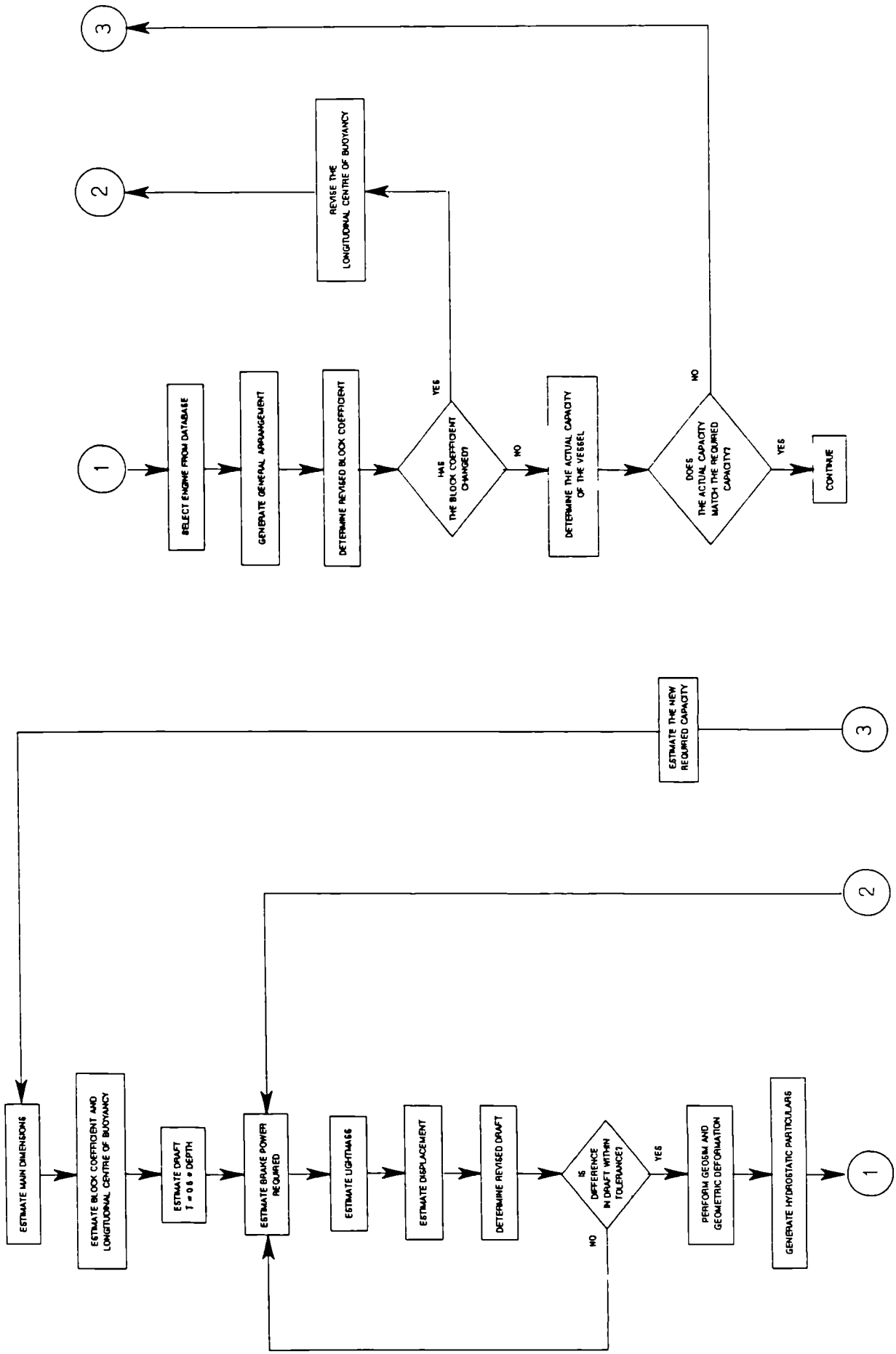


Figure 5.17 The iterative process to determine revised containership dimensions.

design draft has been determined, the associated powering data can be used to determine the type of engine to be installed in the vessel and its associated characteristics (overall dimensions etc.) from which the length of engine room can be determined.

In order to determine the installed power and the associated engine speed an examination of the power-rpm-speed data, produced by the powering procedure, is carried out. This is necessary due to the fact that the value of power used in the estimate of the machinery mass is the delivered power, and not the installed power. The information produced by the powering procedure is used to determine the installed power and the association engine speed, at the required design speed, by interpolation of the power and propeller speed data at the required ship speed. The values obtained are used to determine which of the engines contained in a specially developed database of engine particulars are suitable for the application being considered. The engine particulars database, a section of which is shown in Figure 5.18, contains full details of engine particulars, in terms of output, engine speed, specific fuel consumption and main dimensions, for the full range of MAN B+W MC and Sulzer RTA slow-speed diesel engines as specified in [5.23] and [5.24]. The data contained in the database is in the form of the particulars of the vertices of the operating envelope of each engine model (examples of which are shown in Figure 5.19). This information is used to determine whether each of the available engine models is able to operate at the specified output and speed values. Obviously a systematic examination of every single engine contained in the database will usually produce range of suitable engines from which a single selection has to be made. There are a number of possible criteria against which the final selection of the engine can be made, including specific fuel consumption and overall engine dimensions. As both of these factors are of considerable importance to the successful design and operation of the vessel, it was decided to develop a measure of merit which combined both specific fuel consumption and the overall length of the engine to enable a choice of engine to be made from the available alternatives. The technique adopted allows the emphasis on both the fuel consumption and engine size aspects to be changed so as to influence the final engine selection. If no weighting is assigned to either the specific fuel consumption or the engine length criteria then equal importance is attached to each with the result that the engine which is the best compromise with respect to both fuel economy and minimum physical length will be selected for installation in the vessel.

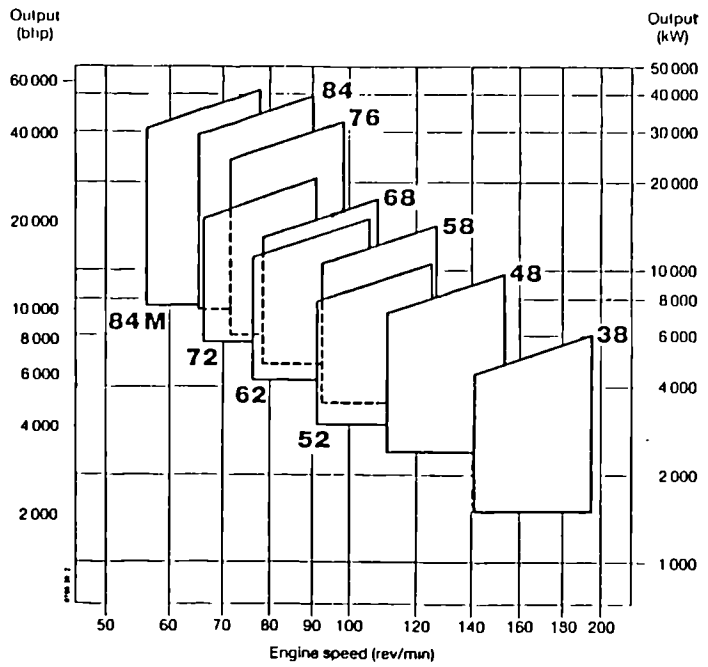


Figure 5.19 Engine operating envelopes of the Sulzer RTA range of slow-speed diesels.

TYPE : SLOW_SPEED M.A.N.-B+W L50MC

L1	L2	L3	L4
	REVS/MIN		
133	133	109	109
	SFOC (g/BHPh)		
126	122	126	122

CYLINDERS	POWER (BHP)				ENGINE LENGTH (M)
4	6200	5000	5080	4080	5.670
5	7750	6250	6350	5100	6.560
6	9300	7500	7620	6120	7.450
7	10850	8750	8890	7140	8.340
8	12400	10000	10160	8160	9.230

FOUNDATION WIDTH	MIN. HEIGHT	SHAFT C.L. ABOVE T.TOP
3.816	8.304	1.054

Figure 5.18 An example from the engine particulars database.

2.3.4.2 Determination of the length of the engine room.

In order to determine the length of the engine room it is assumed that the length is a direct function of the length of the main engine as determined above, although it is appreciated that a number of additional factors should be taken into account such as the type and position of power take-off devices, auxiliaries, services etc., when attempting to determine the size of a machinery space. For the purpose of the ship design system it was considered reasonable to assume that the engine room length is equal to the overall length of the engine multiplied by a factor of 2.20. An examination of existing containership designs showed that this factor was quite reasonable and that methodology adopted would produce a fairly good approximation to the required length of the engine room (with this value being adjusted to take account of the frame spacing of the vessel). It should be noted that in reality the length of the engine room for a given engine length will decrease as the engine room is moved forward along the vessel and more tank top area becomes available, but in the context of the design system considered here it is assumed that this figure of 2.2 is applicable regardless of engine room location.

2.3.4.3 Determination of the location of the engine room.

It can be appreciated that the general arrangement of the profile of the vessel is not only dependent upon the length of the engine room but also its exact location along the length of the vessel. This location is primarily dependent upon the breadth of engine room tank top required in order to accommodate the engine with its associated minimum clearances. The approach developed for inclusion in the system proceeds by locating the engine at the extreme aft end of the vessel and then gradually moving it forward along the vessel until the required breadth of tank top is obtained, as shown in Figure 5.20. In order to enable the breadth of the tank top to be determined at various locations along the length of the vessel, it is obviously necessary to first of all fix the height of the engine room tank top above the base of the vessel. The selection of the height of the engine room tank top could of course have been a fairly arbitrary decision, but it was eventually decided to relate the selection of this height to the factors which affect it in practice. The main consideration when attempting to determine the height is the alignment of the propeller shaft, with the height being chosen so as to ensure that the shaft is parallel to the baseline of the vessel, as shown in Figure 5.21. As at this stage in the proceedings the diameter of the

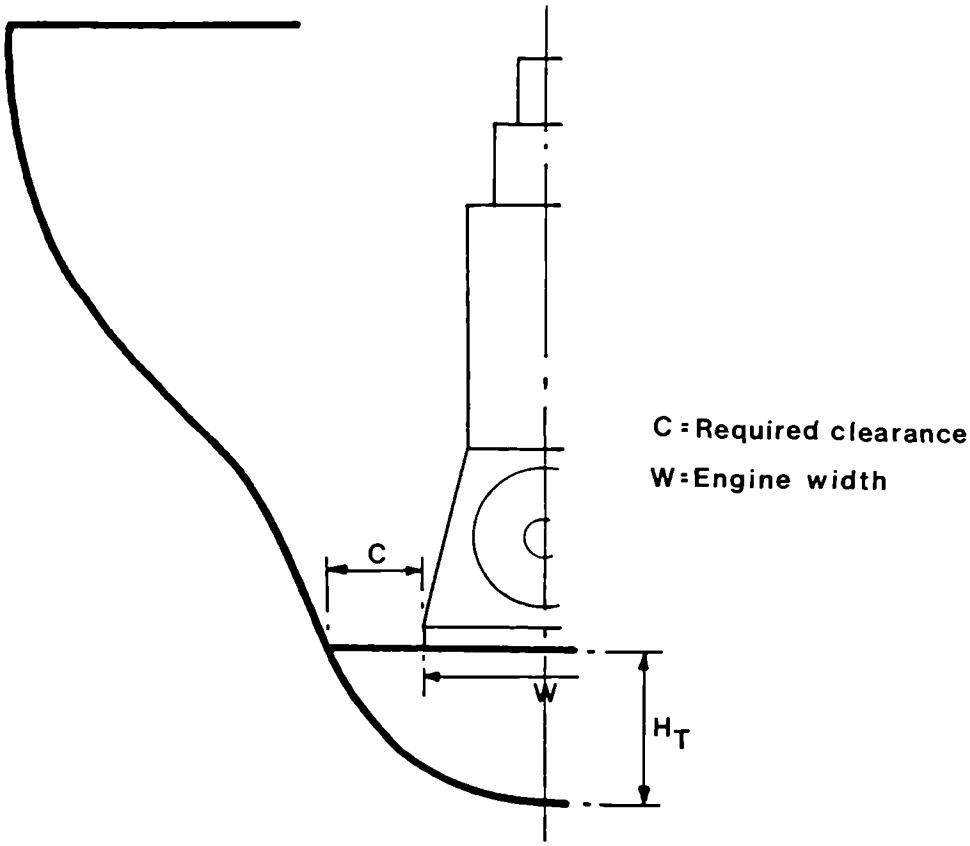


Figure 5.20 The required clearance at the engine aft end.

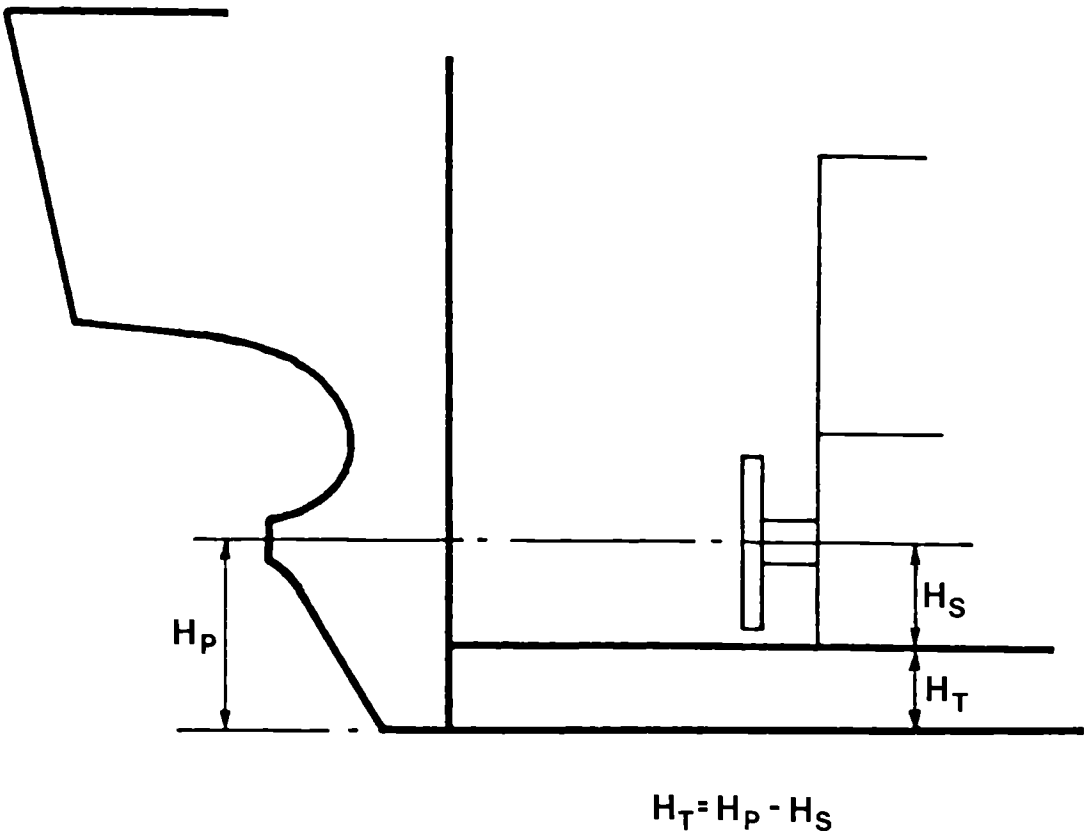


Figure 5.21 Determining the vertical location of the main engine.

propeller is already known, together with its position in the aperture, the required height of the shaft centreline, and hence the output shaft of the engine, can also be determined. The required height of the tank top can then be obtained by simply taking the height of the engine output shaft above the engine base from the height of the propeller shaft above the ship base, with the figure obtained being rationalised to make it more realistic.

Having decided upon the required tank top height in the engine room it is possible to generate the offsets of the hullform at this height above the base. The position of the aft end of the engine can then be determined by gradually moving the engine forward until the required minimum clearances are achieved as described previously. In the context of the ship design system, it was decided to adopt a figure of 1.20 metres for the required clearance as shown in Figure 5.20, this being suggested during the knowledge elicitation sessions discussed earlier.

Knowing the length of the engine room and the location of the engine along the length of the vessel, it is possible to determine the required location of the engine room boundaries by consideration of the position of the engine itself within the machinery compartment. To achieve this it has been assumed that the aft end of the engine is positioned at a location which is some fixed proportion of the engine room length from the aft boundary of the compartment, as indicated in Figure 5.22. Having determined the furthest aft location of the aft engine room boundary, there is one further process to be carried out in order to finally arrive at the location of the engine room and hence complete the profile general arrangement. This involves rationalising the engine room position to match those components of the profile arrangement already determined, such as the hold lengths and the location of the peak boundaries. Initially, this involves comparing the location of the aft peak bulkhead with that of the aft engine room bulkhead. If it is found that the furthest aft location for the aft engine room boundary is aft of the aft peak bulkhead, then the engine room is moved forward until the two bulkheads coincide. If the aft engine room bulkhead has to be positioned forward of the aft peak bulkhead there are two options available. Firstly, if the distance between the two is not too great then the aft peak bulkhead can be moved forward until the two coincide. Alternatively, if the distance between the bulkheads is considerable then the distance between them can be altered so that one or more of the cargo holds is located aft of the machinery space. It should be noted however that all of the operations described above result in the aft engine room

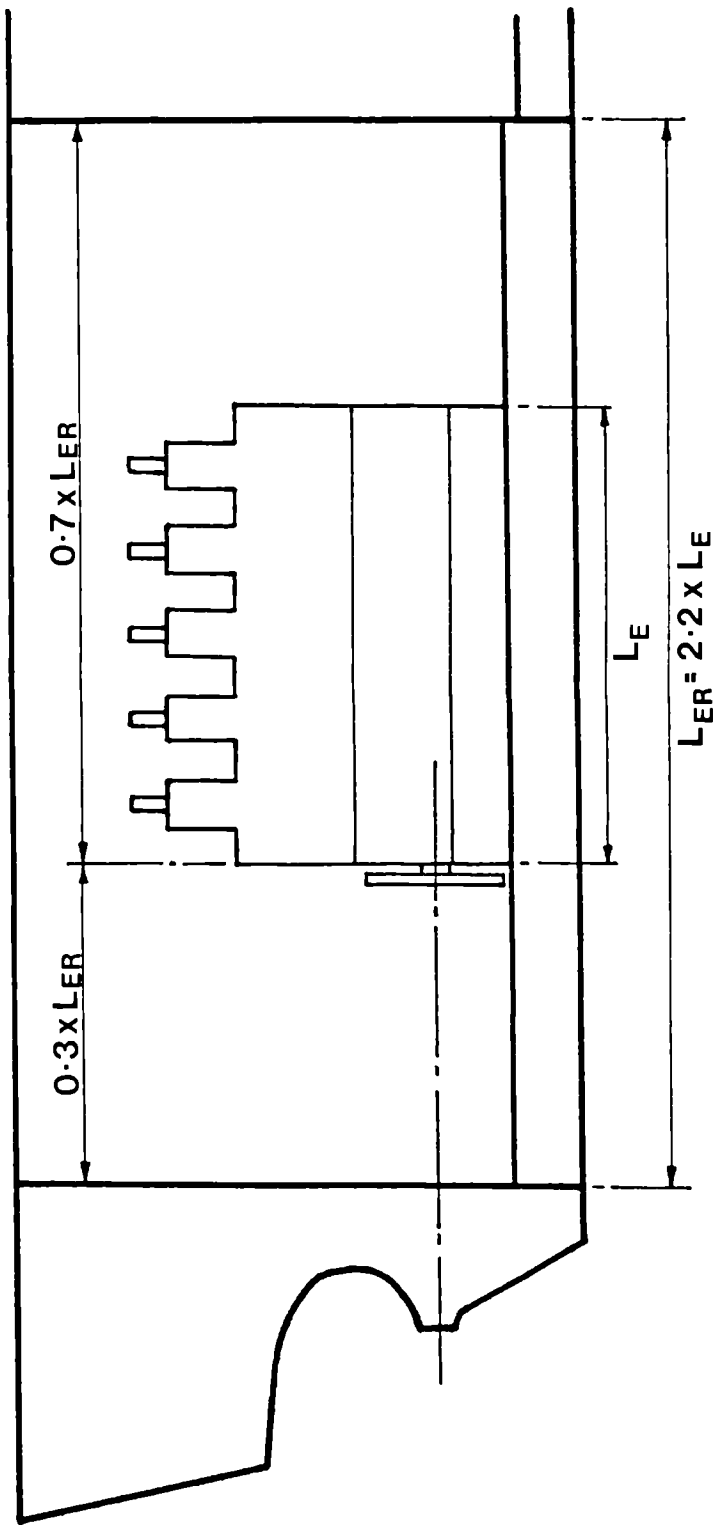


Figure 5.22 Assumed position of the engine in the machinery space.

bulkhead either remaining in the same position or being moved forward, therefore maintaining the required structural clearances previously discussed. The process for obtaining the final engine room position is shown diagrammatically in Figure 5.23.

2.3.5 Determination of actual required length and breadth of the vessel.

The series of operations described in the above sections, results in the complete profile layout being defined with the size and locations of all of the cargo spaces, the peaks and the machinery space having been determined. At this stage it is necessary to compare the total length of the vessel, as produced by a summation of all of the generated spaces, to that generated by the preliminary dimensions generation procedure. On almost every occasion it will be found that the actual length of the vessel as calculated will be different to that previously estimated due to the assumptions implicit in the procedure adopted for generating the preliminary dimensions. It is assumed that this revised ship length will be a more realistic figure as its derivation is based upon a detailed analysis of the required layout of the vessel and takes into account such considerations as the type of cargo handling equipment installed on the vessel (if any), the size and location of the machinery space, the arrangement of hatches and holds, and the type of cargo stowage system specified, with their associated effects on the length of the vessel. To account for the change in the assumed length of the design proposal at this stage, it is necessary to modify the contents of the hullform description database to reflect the alteration to the main dimensions of the vessel. The update of the database is achieved by means of the geosim variation procedure described previously. It is also necessary to modify the hullform of the vessel in terms of its block coefficient and centroid position as these parameters are both functions of the length of the vessel. The required modifications to the hullform are achieved by means of the deformation procedure described previously, although it is appreciated that in practice the possibility of adding parallel middle body to the vessel would be considered.

Having defined the arrangement of the profile of the vessel, and determined the required vessel length and modified the hullform description to suit, the next stage in the development of the overall general arrangement is to consider the arrangement of the vessel in plan view, that is, the layout of the various decks and horizontal boundaries.

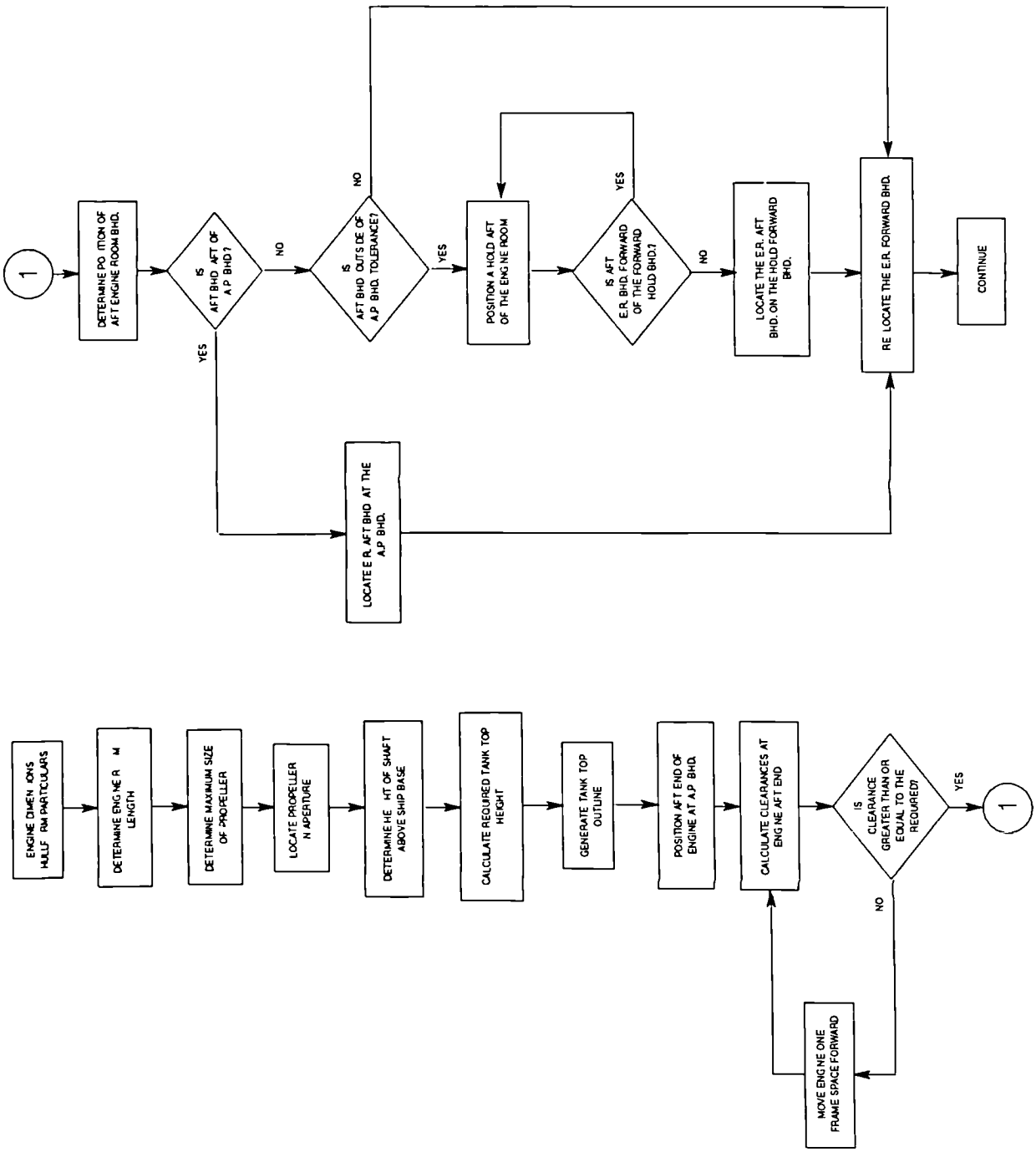


Figure 5.23 The process for determining the position of the machinery space.

2.3.5.1 Arrangement of the cargo hatches.

On a containership, the layout of the uppermost deck determines the number of containers which can be loaded into the holds of the vessel due to the fact that the containers can only be stowed within the line of the hatches and cannot be moved horizontally once they are within the boundaries of the hull. It is therefore of great importance to maximise the number of container slots which can be accommodated within the hatchways, thus requiring that the hatchways be as large as practically possible. In practice, the maximum width of a hatchway will be usually be governed by strength considerations but operational aspects may also have to be considered.

The main consideration when determining the breadth of hatchways to be accommodated is that of hull girder strength, both in terms of longitudinal and torsional strength. Longitudinal strength considerations require that sufficient material is incorporated into the deck region so as to balance the material to be found in the high strength double bottom regions of containerships. The inclusion of sufficient deck material can often be achieved by means of a box-type structure outboard of the hatches and deep box girders between adjacent hatchways, with higher tensile strength material often being used in the upper deck regions of such vessels. The use of box-type members in the design of containerships also contributes towards improving their torsional strength and reducing the racking effects of the hull girder. The number of hatches across the breadth of a vessel is not only dependent upon the need to incorporate deep deck girders for hull girder strength, but also upon the requirement to maintain the weight of hatch cover panels below the maximum which can be lifted by the container cranes either carried on the vessel or to be found in ports around the world. Hatchways which have very large spans will require high strength hatch covers to to support the loads imposed by the deck-stowed containers, with this in turn leading to an increase in the weight of hatch cover panels. The need to restrict the weight of hatch cover panels to around 31 tonnes, will result in two, three and even four hatches across the breadth being found on some container carrying vessels. Large single hatches can also cause problems when considering the operational aspects of containership design, in that it is more difficult to optimise container stowage arrangements in order to avoid problems, such as overstow, when there is only a single hatchway in each hold. Multiple hatch arrangements permit the cargo to be grouped so that individual hatches or groups of hatches contain cargo to be discharged at a single port of call, thus avoiding the problem of having to move all of

the deck cargo in order to discharge cargo stowed in the holds.

In view of the considerations outlined above, it was decided that the ship design system described here would generate proposed upper deck layouts based upon the logic involved in ensuring that both strength and operational aspects were satisfied. First of all, experience indicated that it was reasonable to assume that the strip of deck outboard of the hatches would provide adequate longitudinal and torsional strength if it was made equal to 10% of the overall breadth of the vessel, as shown in Figure 5.24. It was further decided to relate the number of hatches across the breadth of the vessel to the number of rows of containers to be accommodated according to the schema shown in Figure 5.25. As can be appreciated, this approach can only be adopted when the required number of container rows at the point under consideration is known, as is the case at the middle part of the vessel (determined from the preliminary dimensions procedure). Towards the ends of the vessel the number of rows which can be accommodated will decrease and can only be determined by consideration of the deck outline at the relevant locations. Knowing the locations of the ends of hatches, it is a fairly simple process to interrogate the hullform description data to determine the breadth of the upper deck at these points and then determine the number of rows of containers and hence hatches which can be accommodated across the vessel. In order to calculate the width of vessel required for a particular hatch arrangement, it is necessary to consider the required gaps between the individual containers in the transverse direction and the associated structural clearances. As before, assumptions are made regarding the required gaps and clearances, with the figures used in the design system being shown in Figure 5.26.

2.3.6 Interactive design of the general arrangement.

The previous sections have described the logic utilised by the system to develop an initial general layout in terms of the size and location of the cargo spaces, the machinery space and the peaks, and also the arrangement of upper deck hatches and cargo handling equipment. Although the methodology used by the system in arriving at a proposed arrangement is based upon current practice and incorporates considerable expertise and knowledge provided by the various knowledge elicitation exercises described earlier, it was realised that on some occasions the system user might wish to create his own general arrangement for use in the investigations. To enable the user to do this, a number of procedures were developed by the author which incorporate

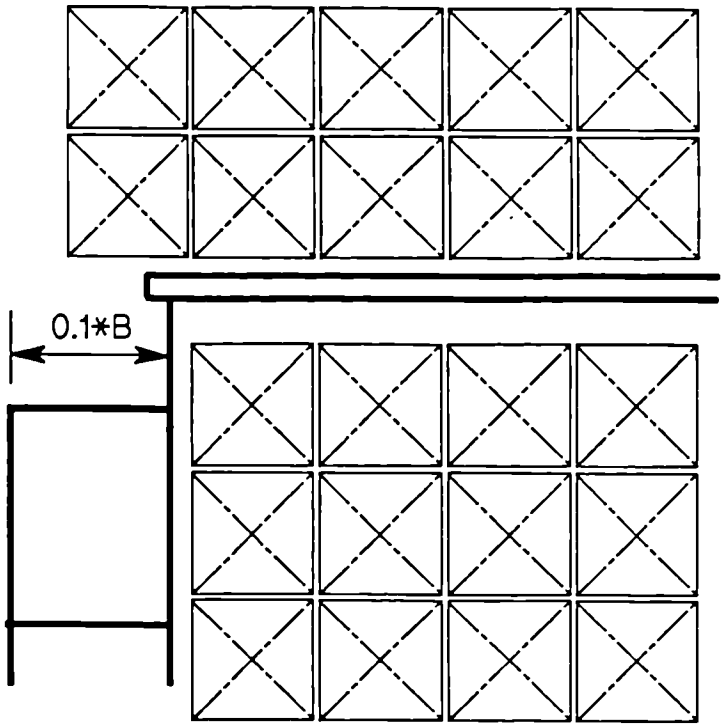


Figure 5.24 The width of deck outboard of the hatches.

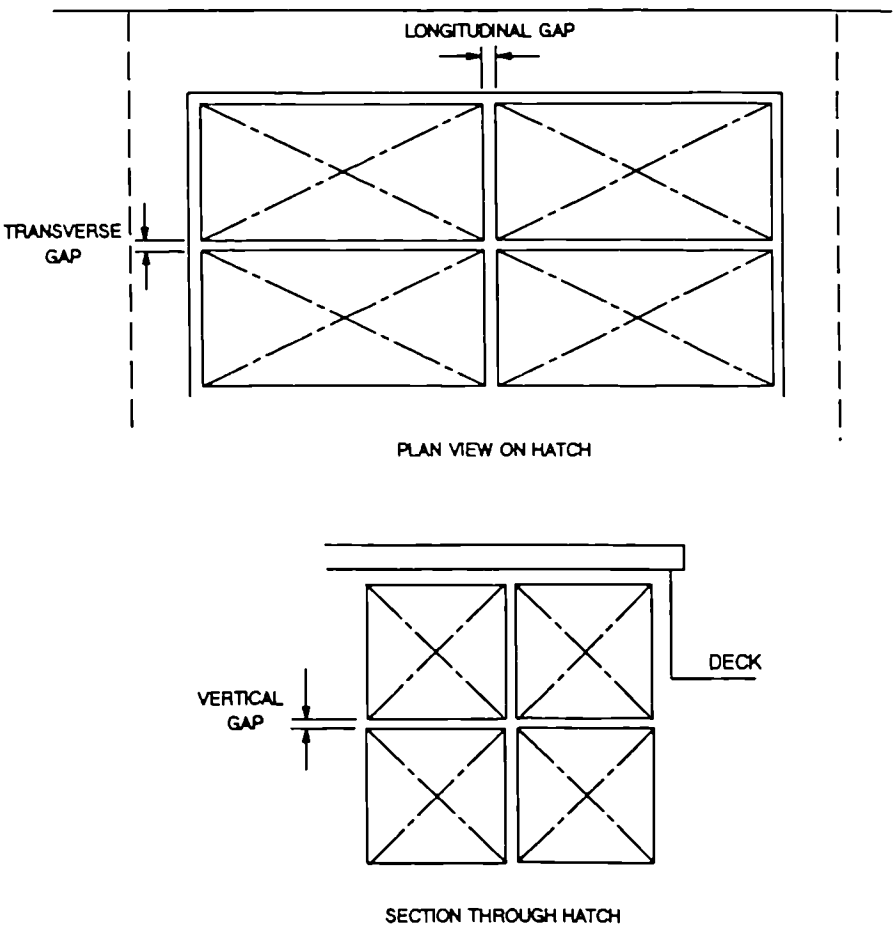


Figure 5.26 Definition of the between-container gaps.

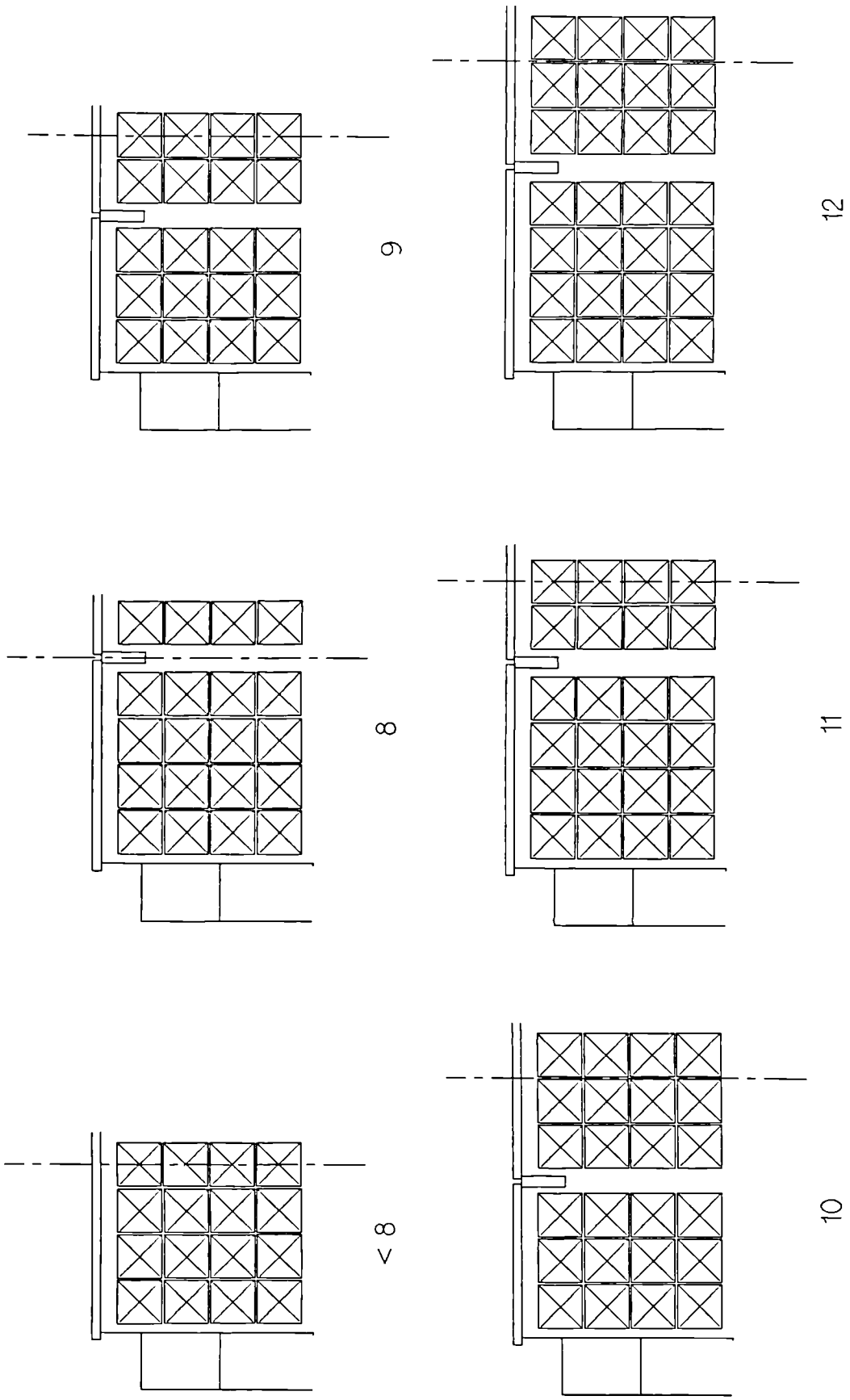


Figure 5.25 Schema for determining the number of hatches across the breadth of the vessel.

interactive graphics to permit the creation and modification of general arrangements in real-time using a collection of compartment boundary primitives.

A number of interactive general arrangement design systems have already been developed, with the emphasis being on the design of naval craft ([5.25], [5.26], [5.37]). Although such systems require the user to have a fairly detailed knowledge of the proposed layout before the interactive definition can commence, they do provide the ability to define hundreds of individual compartments and develop highly detailed general arrangements. Although this standard of definition may be necessary in the design of complex naval vessels, it was not considered to be a requirement for a system concerned mainly with the definition of an arrangement which illustrates whether a vessel has sufficient cargo spaces and tankage for the profitable and safe operation of the vessel.

2.3.6.1 Interactive layout definition.

The arrangement of a vessel of any type can be considered as being built up from a series of structural elements which provide for its strength, its ability to carry a payload, to be operated correctly and for its safety. The basic layout definition process can be considered as that of deciding upon the disposition of these structural elements within the confines of the available hullform. In general, the various levels of structural element functionality can be expressed diagrammatically as shown in Figure 5.27. With reference to the diagram, the tertiary and, to a large extent, the secondary levels of structural elements are normally considered at the more detailed levels of the design process as these items are governed by Classification Society requirements relating to detailed structural design and scantling determination. The layout definition process considered here is more concerned with the primary level of structural elements including items such as decks, flats, bulkheads, inner hulls etc., together with some secondary elements such as watertight/oiltight girders and floors in double bottom regions where these form the boundaries of individual compartments. It is assumed that once the locations of these elements have been decided upon, they will not be changed at the detailed structural design stage, as modifications at this point will normally be restricted to the variation of frame or longitudinal spacing in an attempt to minimise weight and/or cost [5.27].

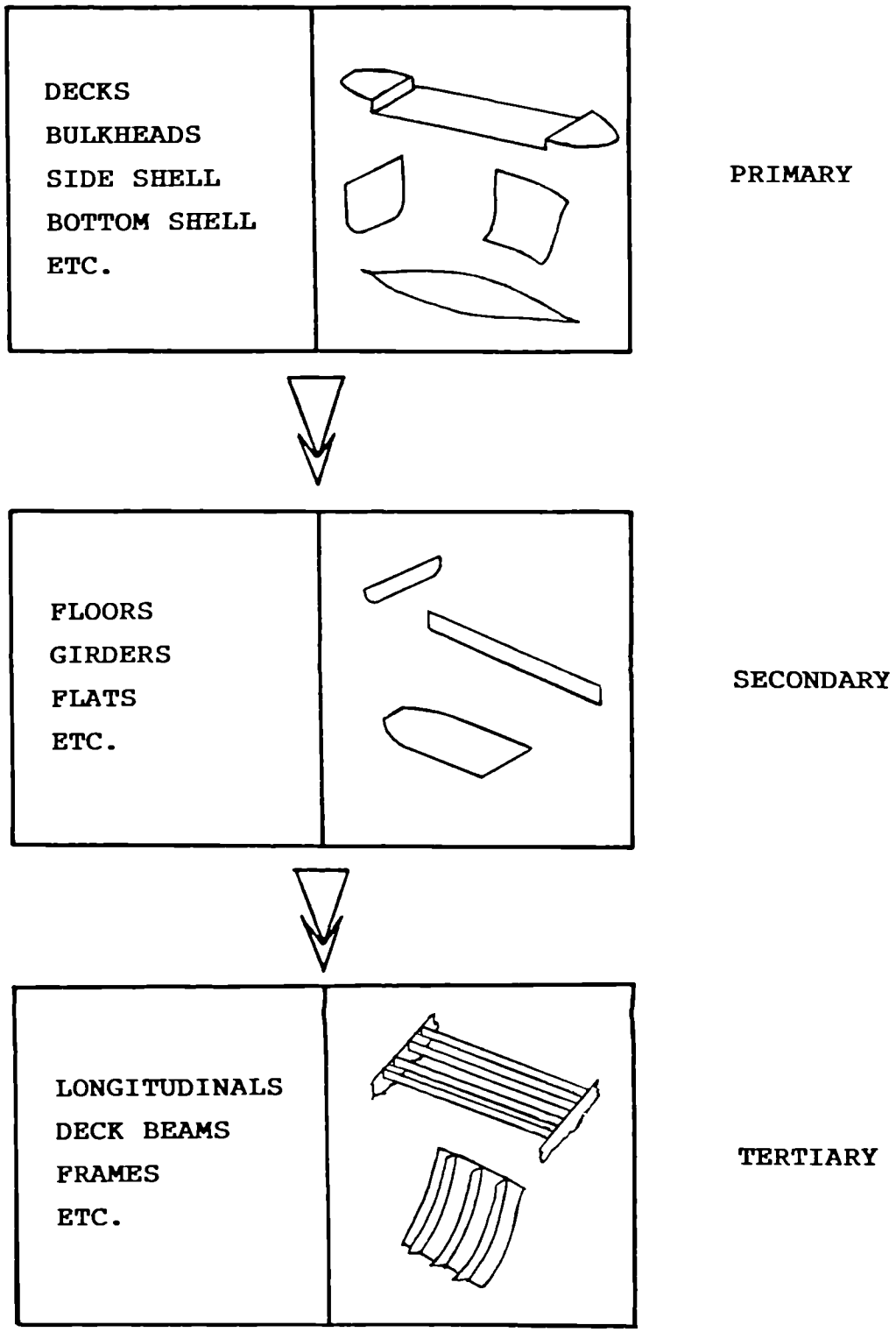


Figure 5.27 Assumed structural element hierarchy.

2.3.6.1.1 Boundary element types.

The interactive layout definition procedures were developed so as to provide the system user with the ability to create realistic representations of internal layouts by means of the manipulation of a set of geometrical primitives which represent the various structural boundaries found on actual vessel types. An examination of merchant vessel general arrangements indicated that any internal layout for a merchant vessel can be considered as comprising a relatively small number of basic elements, which, depending on their orientation, size and function, are usually classified as decks, bulkheads, flats and so on. It was therefore considered reasonable to assume that quite realistic representations of internal layouts for a wide range of merchant vessels could be produced by simple manipulation of a fairly small set of basic geometrical elements. The elements subsequently developed for inclusion in the ship design system are shown in Figure 5.28, together with examples of their shipboard equivalents. The interactive layout definition routines of the design system enable the user to develop an internal arrangement using the boundary representations described above. In order to increase the flexibility of this part of the design system, it was decided to provide the user with a choice of three methods of defining an internal layout; interactive keyboard definition, interactive sketch definition and interactive free-hand definition.

2.3.6.1.2 Interactive keyboard definition.

This mode of input enables the user to create a layout representation by typing relevant commands from the computer keyboard. These commands define the location and extent of the various structural boundaries which make up the general arrangement.

This mode of input is ideal if the user has knowledge of the desired layout in terms of the exact locations of the relevant decks, bulkheads, flats etc.

2.3.6.1.3 Interactive sketch definition.

This mode permits the user to define an internal arrangement from a sketch of the design profile and deck plans. The definition is achieved by digitization of the locations of the various structural boundaries, which combine to make up the required general arrangement, from the digitizer tablet. As with the hullform definition

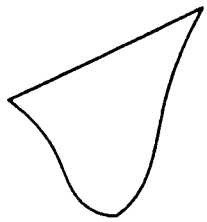
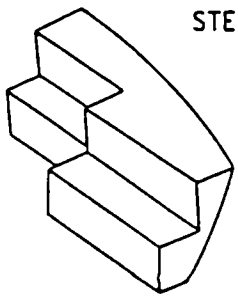
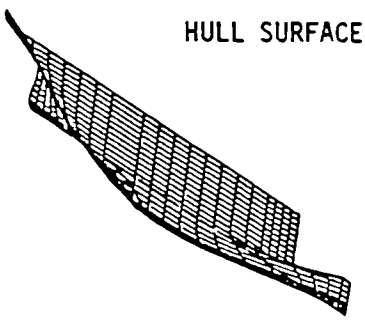
BOUNDARY TYPE :	EXAMPLE :
MULTI-ORIENTATION VERTICAL	 TRANSVERSE BULKHEAD
MULTI-ORIENTATION HORIZONTAL	TANK TOP 
COMPLEX 3-DIMENSIONAL	STEPPED SIDE TANK 
DOUBLE CURVATURE SURFACE	HULL SURFACE 

Figure 5.28 The boundary elements avaialable for the creation of general arrangements.

procedures described previously, the sketch arrangement could be obtained from a variety of sources such as the technical press, and more importantly, could be the user's own interpretation of a layout to match the design requirements.

2.3.6.1.4 Interactive free-hand definition.

This method of definition allows the user to build up an arrangement interactively on the graphics screen by using the digitizer mouse to indicate the location of decks, bulkheads etc., on a profile of the vessel displayed on the graphics screen. Menu options are provided for the insertion, deletion and modification of these boundaries on both profile and plan views of the vessel. Other options provide for the display of the outlines of selected boundaries together with their associated geometric properties such as enclosed area, centroid location and critical dimensions.

A required internal arrangement can be developed interactively either by exclusive use of one of the above methods, or by using any combination of all three. The procedures provided allow a realistic representation of an internal arrangement to be developed in a very short time.

2.3.6.1.5 Boundary relationships.

An examination of any ship general arrangement will reveal a number of basic relationships between the various structural boundaries with the possibility that these relationships could be utilised to the benefit of the system user involved in the development of an internal arrangement.

The most obvious physical relationships exist between those boundaries which coincide with the termination of other boundaries, as at deck/bulkhead intersections as illustrated in Figure 5.29. The recognition of such relationships, and their incorporation into the layout definition procedures, considerably reduces the time required to modify an arrangement in order to allow an evaluation of alternative internal configurations to be undertaken. The system has the ability to recognise basic relationships between the various boundary elements with the results that changes made to individual boundaries are automatically reflected in modifications to the position or extent of associated elements. Figure 5.30 shows the overall effect on a given layout of the user changing the location of a single boundary element, such as the tank top, thus illustrating the way in which a topological representation can be used to assist the

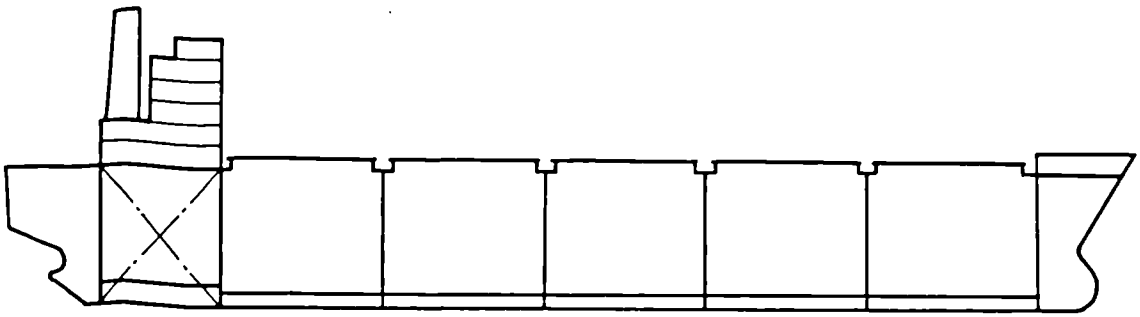


Figure 5.29 Illustration of the relationships between individual boundaries.

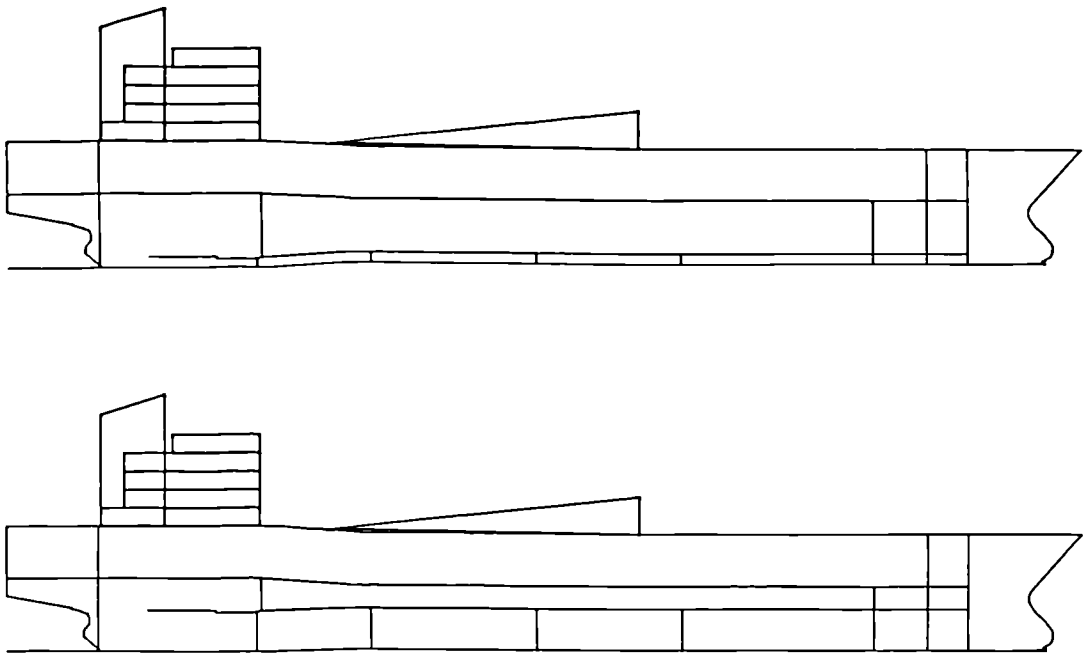


Figure 5.30 The effect on a layout of modifying a single boundary element.

system user develop an internal layout.

2.3.6.1.6 Definition of erections.

The interactive approach outlined above has been further adapted to permit the definition of erections above the main hull envelope, such as accommodation blocks, forecastles, funnels etc., so that a more complete picture of the general arrangement of the design proposal can be obtained.

The adoption of an interactive graphics approach permits the user to quickly define proposed erections using boundary elements on a plan view of the relevant erection platform. These boundaries can be used to represent the sides and ends of the erections together with any major internal structural items such as engine casings and stair wells. In addition, the system allows the side shell of the vessel to be extended above the upper deck level so that a true representation of ship-shaped erections can be obtained. The heights, and hence projected areas, of these elements are determined from the knowledge of the relationship between the top of the particular erection and either the erection base or the ship base as specified by the user, as shown in Figure 5.31. The projected areas of the sides, ends, casings etc., are used to arrive at an estimate of the mass of the erections by means of the application of Classification Society rules for the associated plating thicknesses. During the development of the procedure, it was found that the mass of any associated plate stiffening represented only a relatively small proportion of the overall steelmass of an erection, and a decision was therefore made to allow the system user to define the allowance to be made for the mass of the stiffening members so that account could be taken of the variation in stiffening arrangements brought about by localised loadings etc. It should be appreciated, however, that the steelmass particulars can only be estimated for erections which can be classified as accommodation areas. If the particulars of other erections such as funnels and masthouses required, then the user is required to supply information relating to material thicknesses, stiffening allowances etc., so that the relevant mass calculations can be performed.

Although of no particular use in the context of the design system module being considered here, the centroid and steelmass data for the erections is used by other modules of the complete conceptual ship design system and in particular by the steelmass estimation module ([5.29], [5.30]). The links with the other modules of the

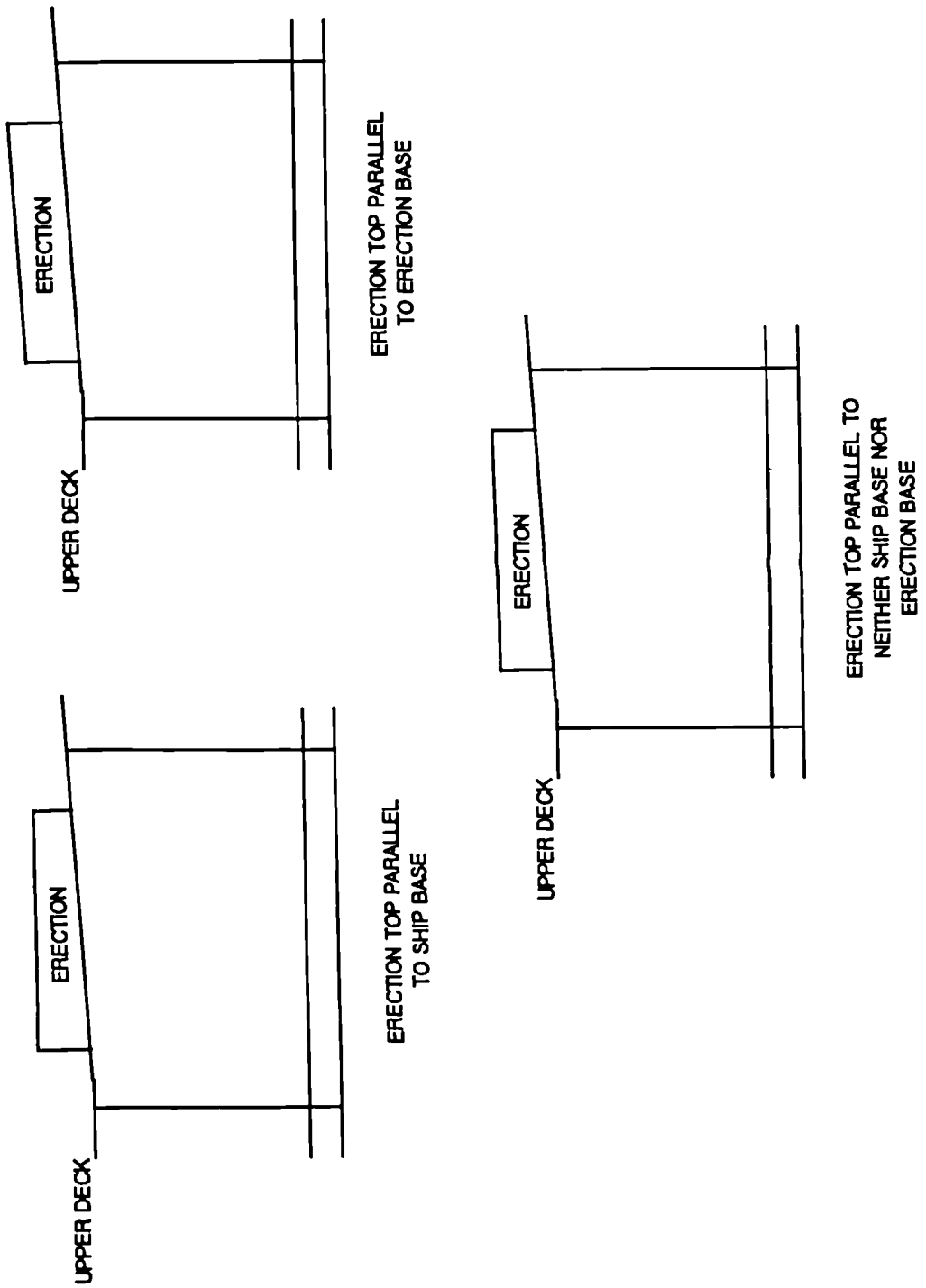


Figure 5.31 The possible relationships between an erection base and its top.

system will be discussed at a later stage.

By combining the definition of the erections with that of the internal layout of the hull, a complete picture of the proposed general arrangement for any vessel can be obtained. The general methodology adopted to provide the basis of the interactive layout definition procedures means that they can be used to define the general arrangement of vessels of virtually any type and are not restricted to the development of containership proposals. An example of the application of the procedures to the development of the internal arrangement of a Ro-Ro vessel is given in [5.31] (which can be found in Appendix I), thus illustrating the flexibility of the procedures developed by the author for inclusion in the conceptual ship design system. Figure 5.32 illustrates a layout generated using the interactive procedures described above and is indicative of the quality of the graphical procedures incorporated in the system.

2.4 Determination of the actual capacity of the vessel.

Regardless of which method for the development of an internal arrangement is utilised, either knowledge base proposed or user defined, the next stage in the development of a design proposal is to determine the actual capacity of the vessel, as up until this point it has been assumed that the actual capacity of the proposal is equal to that required by the user. In order to determine the true capacity of the proposal an external procedure, developed by the author, is utilised by the expert system.

Using the information previously generated concerning the arrangement of holds and hatchways and the required gaps between containers, together with the available hullform description, the external procedure is able to calculate the number of containers of the specified dimensions which can be accommodated in the design proposal. The methodology used by this procedure is summarised below.

As a first step, the process involves the generation of a cubic spline description of the relevant hullform definition up to and including the level of the upper deck, with the hold and hatch descriptions being superimposed onto this description. The second stage is to locate the containers in the specified holds. In order to maximise the number of containers carried in a particular hold, a number of basic assumptions are made regarding the positioning of the containers in the hatchways. Firstly, it is assumed that in hatches which are forward of midships the aftermost container bay in

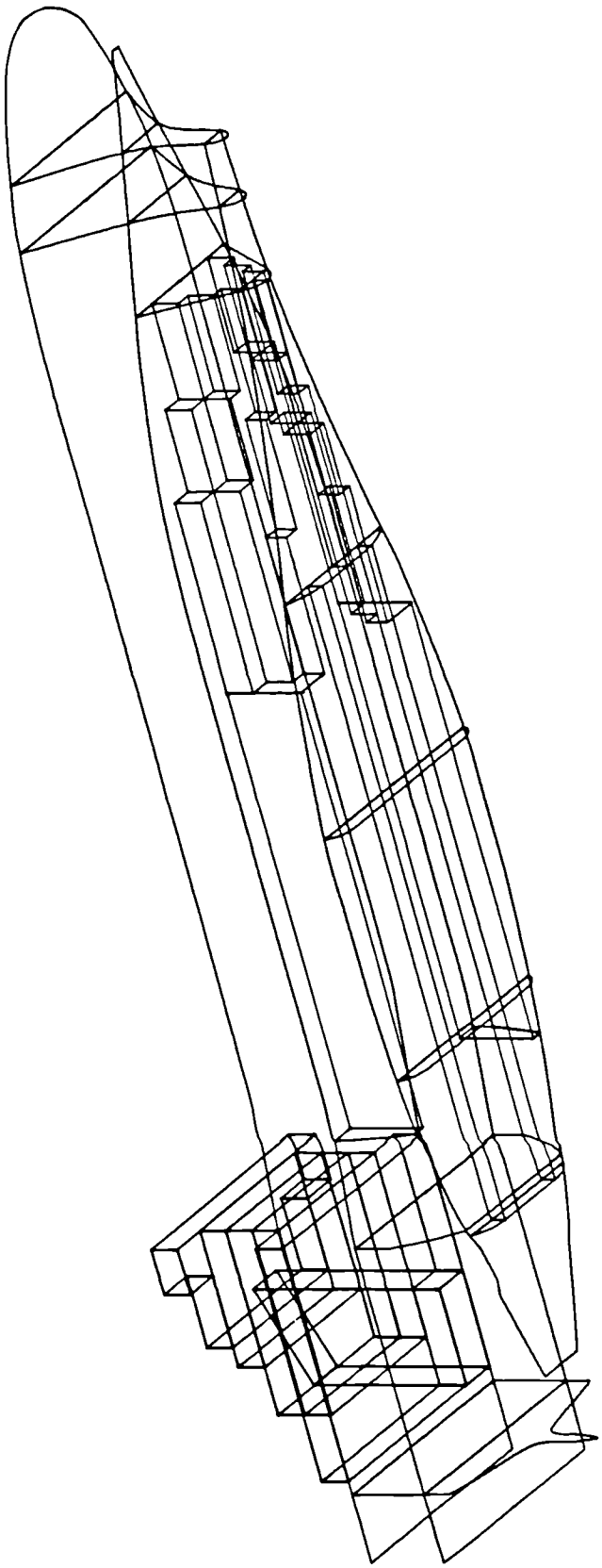


Figure 5.32 An example of a layout defined using the interactive layout generation procedure.

the hatch will be positioned as far aft in the hatch opening as possible, as this will result in the containers being as far aft as possible towards the widest part of the vessel, as indicated in Figure 5.33. Similarly, where the hatch under consideration is aft of midships, the forward most container bay is positioned as far forward as possible towards the widest part of the vessel, as indicated in Figure 5.34.

Having determined the positions of the container bays in the hatchways, the next step is to determine the locations of the rows of containers across the breadth of the vessel. In order to maximise the number of container accommodated the positioning of the container rows is commenced from the most inboard point of each hatchway. For a twin hatch arrangement, as shown in Figure 5.35, this involves positioning the inboard row as close to the inboard hatch side girder as possible, with adjacent rows being located outboard of this one. Hatches which straddle the centreline of the vessel allow two possible approaches to be adopted. If the hatch contains an odd number of container rows then obviously one of the rows will have to straddle the vessel centreline with subsequent rows being located adjacent to this central one, as shown in Figure 5.36. Alternatively, *if there is an even number of container rows in a* central hatch, the first container will be located at a distance of half the transverse between container gap off the centreline of the vessel with the remaining containers being located alongside this one.

Having decided upon the locations of the bays and rows of containers within the specified hatchways, the next step is to determine the vertical stowage arrangement within the holds and to assess the effect of the actual hullform shape on the number of containers which can be accommodated. The process adopted for this investigation involves the generation of a section through the vessel at the critical end of each container bay, the being the forward end of bays in the forward half of the vessel and the aft end of those bays located in the after half of the vessel. Starting at tank top level, containers are added, a tier at a time, working from the centreline outwards until any part of the critical end of the current container lies within a specified distance of the side of the vessel, as shown in Figure 5.37. This minimum perpendicular clearance represents the distance needed in order to accommodate the main side supporting structure of the vessel, such as the side-frames, webs etc.

Once a container in a particular tier has violated this minimum clearance requirment, the next tier of containers is considered, with the process described above being

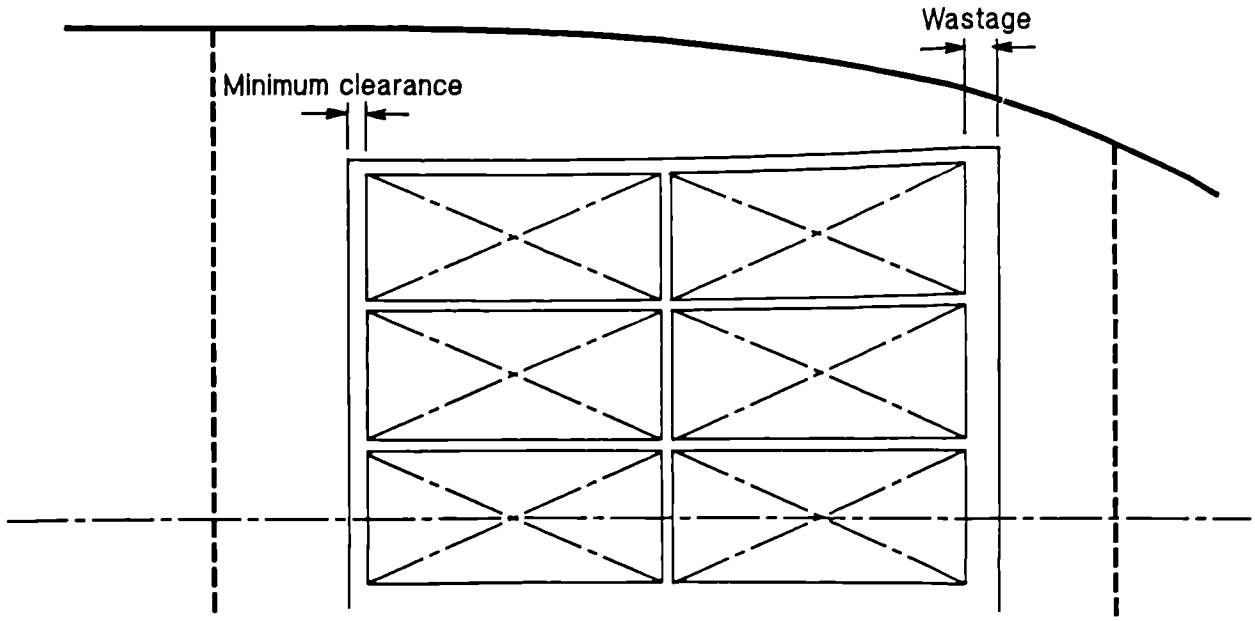


Figure 5.33 Locating containers in a fore-body hatch.

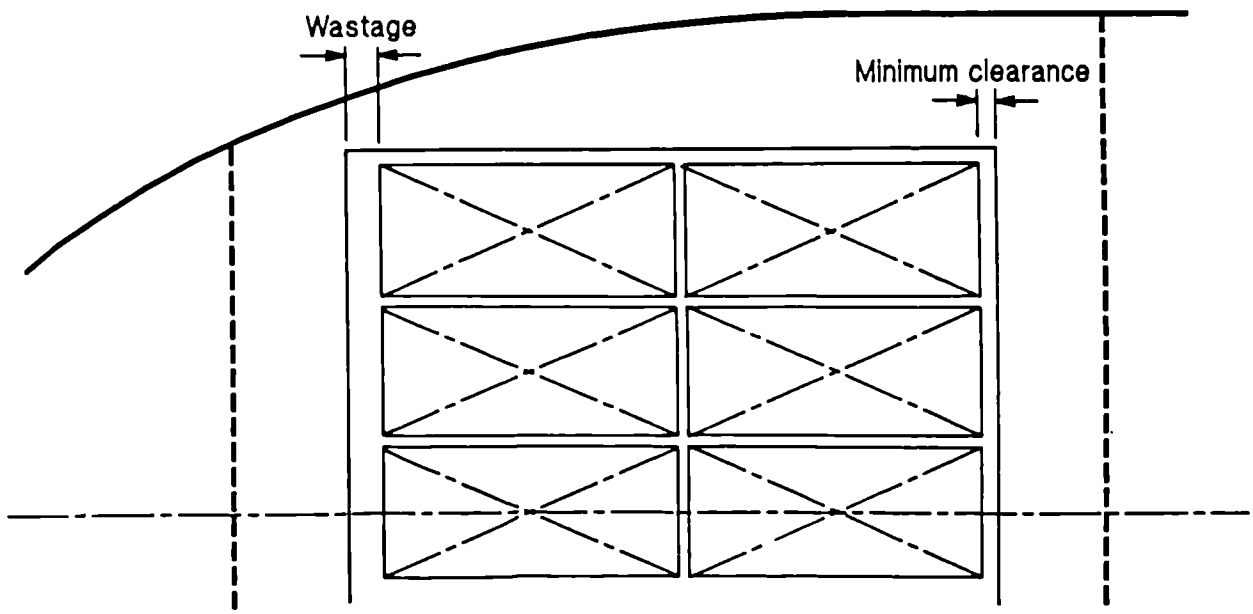


Figure 5.34 Locating containers in an aft-body hatch.

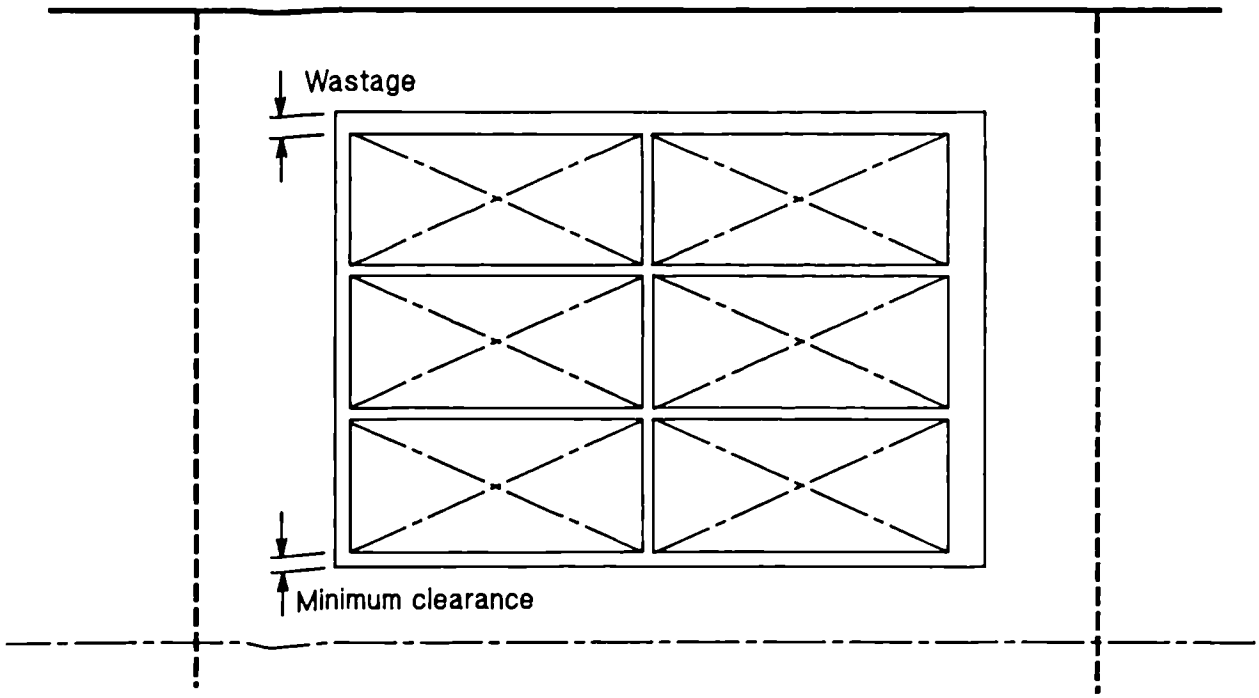


Figure 5.35 Locating containers in a twin-hatch arrangement.

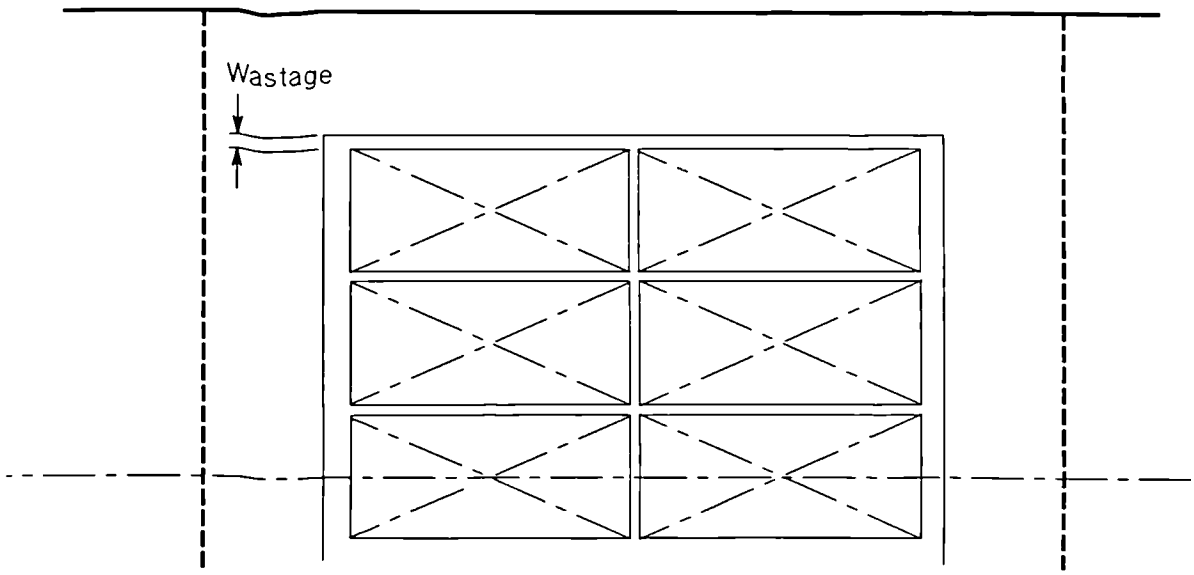


Figure 5.36 Locating containers which straddle the centreline of the vessel.

repeated at this new level.

The whole of the above process is repeated, with the required minimum gaps between adjacent containers being observed, until the current container tier protrudes through the hatch opening and into the hatch coamings. In this case a check has to be made on the required hatch side girder clearances and also on the below hatch cover clearance, as shown in Figure 5.38.

Repeating the above procedure for each of the available holds results in the total under-deck container capacity being determined. It now only remains to examine the on-deck stowage in order to arrive at the total capacity of the vessel.

The on-deck containers are assumed to be located in bays which are vertically coincident with the bays contained in the holds, with the result that an arrangement which has twelve bays below deck will also have the same number of bays above deck. When considering the number of containers across the breadth of the vessel in these on-deck tiers, it is assumed that the rows can extend over the side of the hatchway as the outermost containers will be supported by an arrangement of pillars, as shown in Figure 5.39. The only check which has to be made when arranging the on-deck containers, is that concerning a minimum clearance between the outermost container and the side of the vessel, as shown in Figure 5.39. The number of tiers of containers located on the hatch covers is specified by the system user, with the number normally being limited to three or four through consideration of stability and container securing arrangements.

Having determined the number of containers which can be accommodated above deck for a user-specified number of deck tiers, the total container carrying capacity of the vessel can easily be calculated.

As mentioned previously, the aim of the exercise described in the previous sections is to determine the actual container capacity of the design proposal so that a comparison with the specified required capacity can be made. This comparison will normally reveal that the actual capacity of the vessel is different to that required to some extent. If the actual capacity is within an acceptable tolerance, say thirty containers, then it is assumed that the proposal is suitable for further development. If, however, the difference between the required and actual capacities is greater than the specified tolerance, it is assumed that some form of corrective action is required. In the context

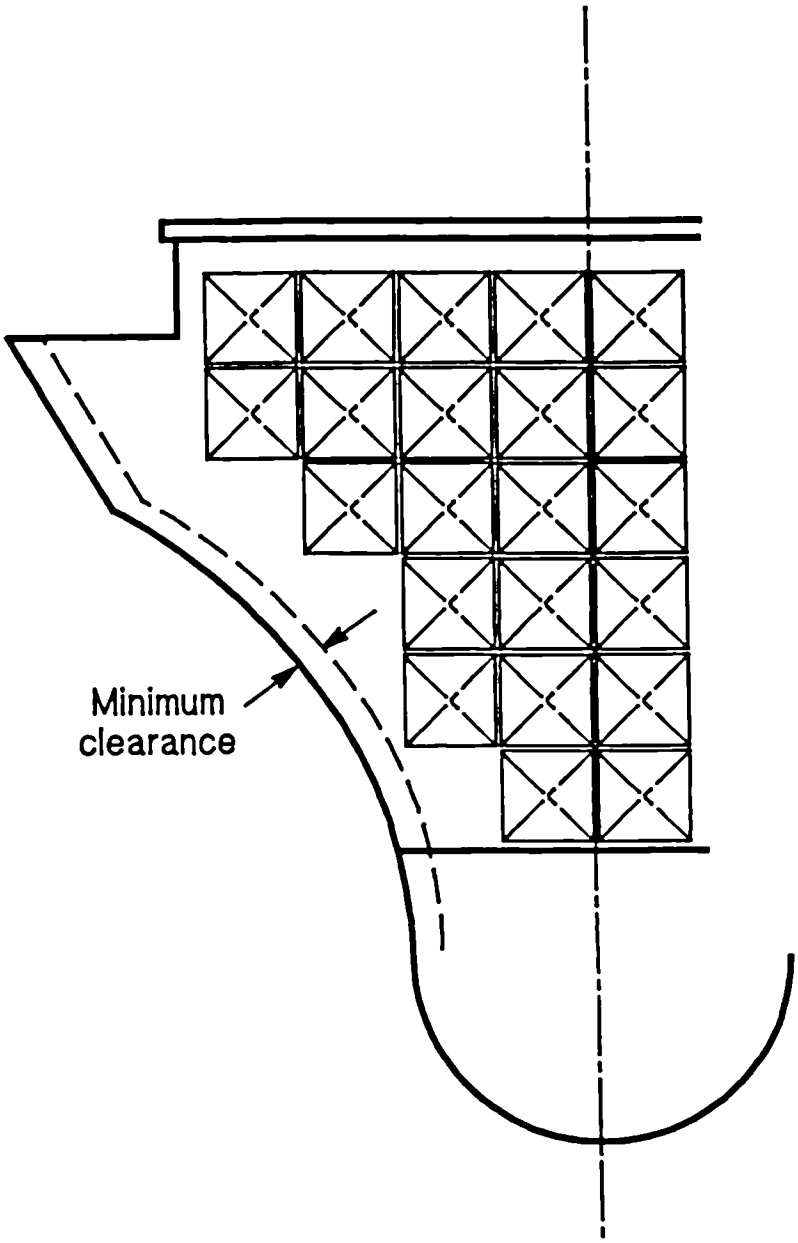


Figure 5.37 Locating containers in the vertical plane.

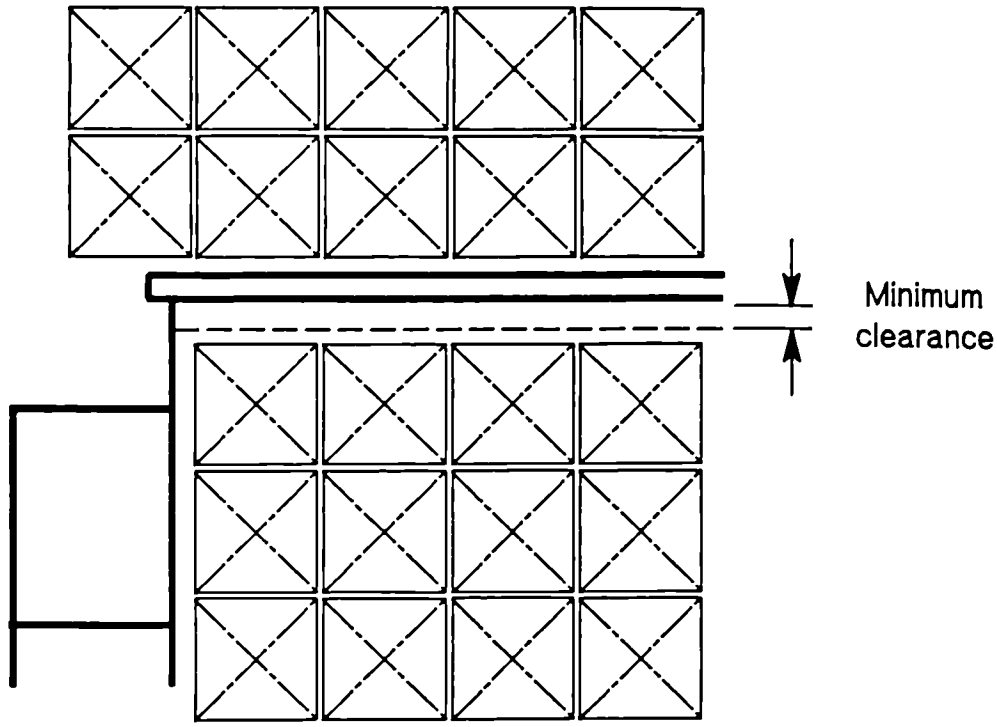


Figure 5.38 Container clearances below the hatch covers.

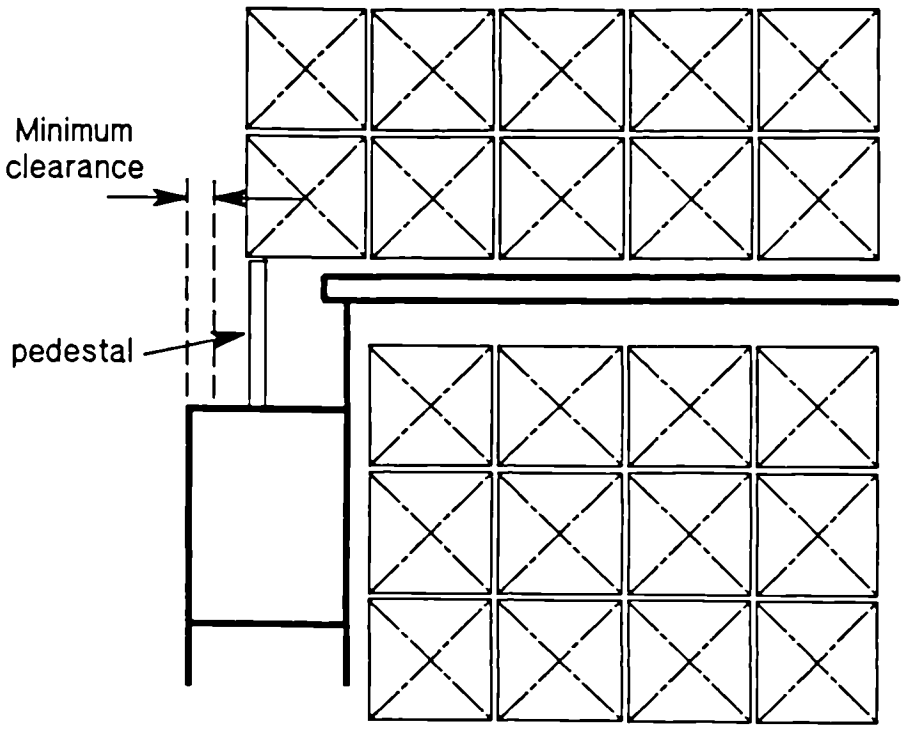


Figure 5.39 Location of the on-deck containers.

of the design system, this action takes the form of modifying the input data to the initial dimensions estimation procedure, as previously described, in order to determine a revised estimate of the required dimensions and the number of bays, rows and tiers, above and below deck. This modified input is in the form of a revised total capacity requirement which reflects the error in the actual capacity as produced by the initial estimate of the vessel dimensions and the associated general layout. This new capacity requirement is determined as follows:

$$\text{New required capacity} = (\text{True required capacity})^2 \ / \ \text{Actual capacity}$$

The above will result in the input to the initial dimension estimation routine being less then the true requirement if the actual calculated capacity is greater than that required, and more than the true requirement if the actual capacity is less than that required. Using this new value as input to the preliminary dimension estimation procedure, the complete process described in the previous sections is repeated in order to arrive at a vessel definition which matches the specification in terms of the number of *containers which can be accommodated.*

The adoption of this iterative approach, as outlined in Figure 5.40, will result in the development of a design proposal which satisfies the basic specification in terms of geometric capacity and hullform characteristics. Once this has been achieved the proposal is assumed to be suitable for further development by other sections of the knowledge base.

2.4.1 Container slot identification.

Assuming that the proposal satisfies the basic requirements of the design specification, it is considered to be suitable for further investigation and development. The first stage in this further development is the identification of the individual container slots which can be accommodated on the vessel. It should be appreciated that the process of determining the capacity of the vessel, as described above, not only results in the total geometric capacity of the vessel being made known, but it also identifies each of the available container slots in terms of its precise location in the vessel as defined by the position of its geometric centroid. Knowing the dimensions of the container to be carried in the slot, knowledge of the geometric centroid location enables the position of the ends and the top and bottom of each container to be calculated. In order that each container slot on the vessel can be referenced, it is

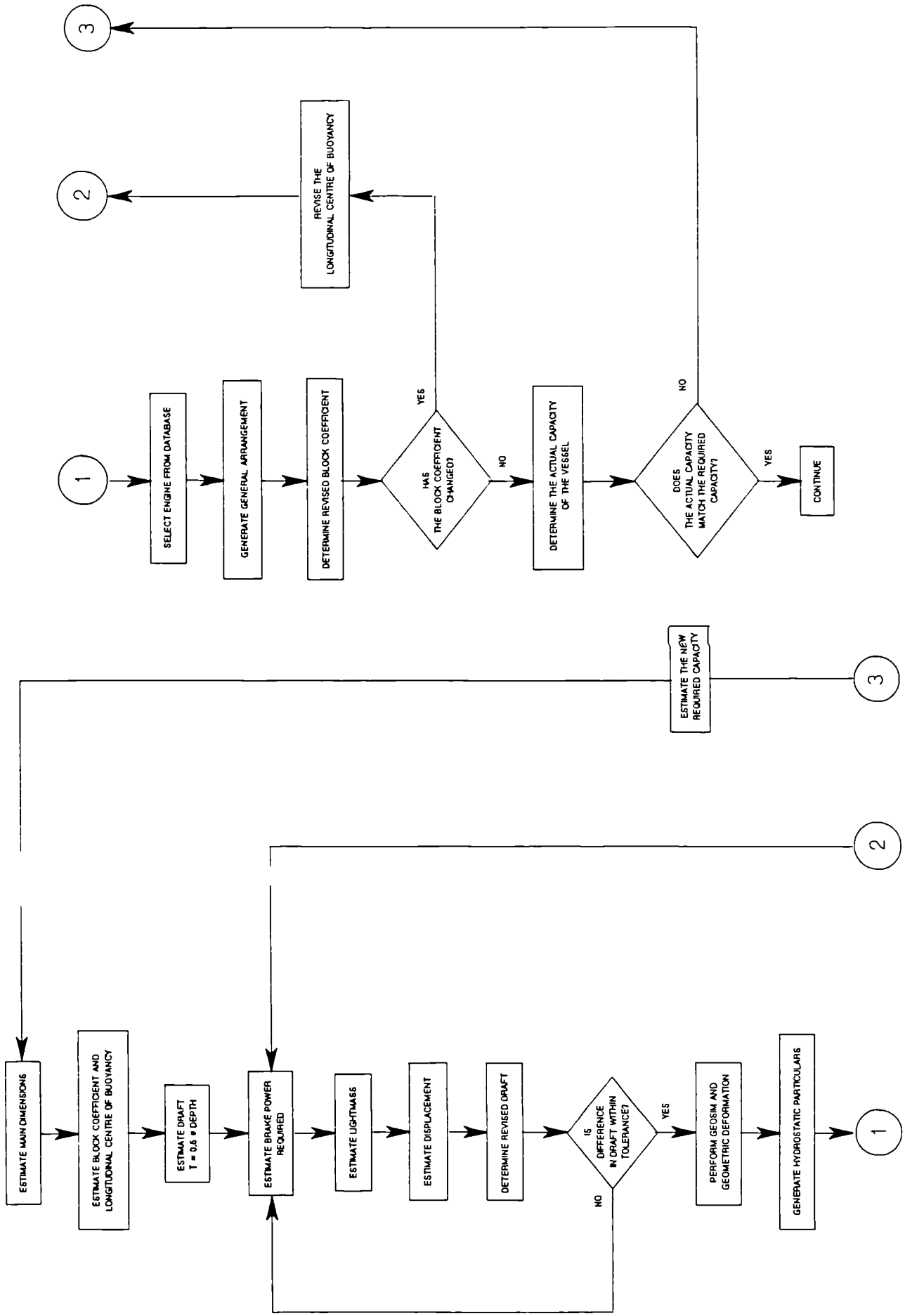


Figure 5.40 The complete iterative cycle to determine containership particulars.

necessary to assign some means of identification to each of the slots. In practical containership design investigations there is a generally accepted convention for the identification of slots onboard containership design proposals, and as one of the aims of the system being developed was to reflect current design practice, a decision was made to conform with this convention for the assignment of individual slot identifiers. The basis of the convention is that each slot on the vessel, above or below the upper deck, is identified by a unique six digit code which indicates in which bay, tier and row, the slot is to be found. The first two digits represent the bay which contains the slot, with the slots being numbered starting at the forward end of the vessel and working aft, as indicated in Figure 5.41. The second pair of digits indicate the relevant tier, as shown in Figure 5.41, with the final pair of digits representing the row number. Thus the exact location of any container slot can be expressed by means of a single six digit identifier, an example of which is given below:

Example: Container **050806**

where:

05 is the third bay from the forward end,
08 is the fourth tier above the tank top,
06 is the third slot off the centreline on the port side of the vessel.

The above representation is particularly useful when evaluating vessel loading conditions, with the masses to be carried in the various slots being assigned on the basis of these identifiers. From this definition the exact location of the slots can be determined and used in the relevant calculations. The loading conditions assessment aspect of the design system will be discussed in some detail later.

As a result of the importance attached to this slot identification convention, a procedure was developed by the author which takes the slot location information previously discussed and transforms it into the six digit identifier format described above.

With each of the container slots identified and their exact locations on the vessel known, graphical procedures are used to enable the system user to obtain a visualisation of the current state of the design proposal in terms of the general layout of the vessel. This graphical representation takes the form of a simple profile of the vessel showing the container bays and tiers above and below deck, together with the rele-

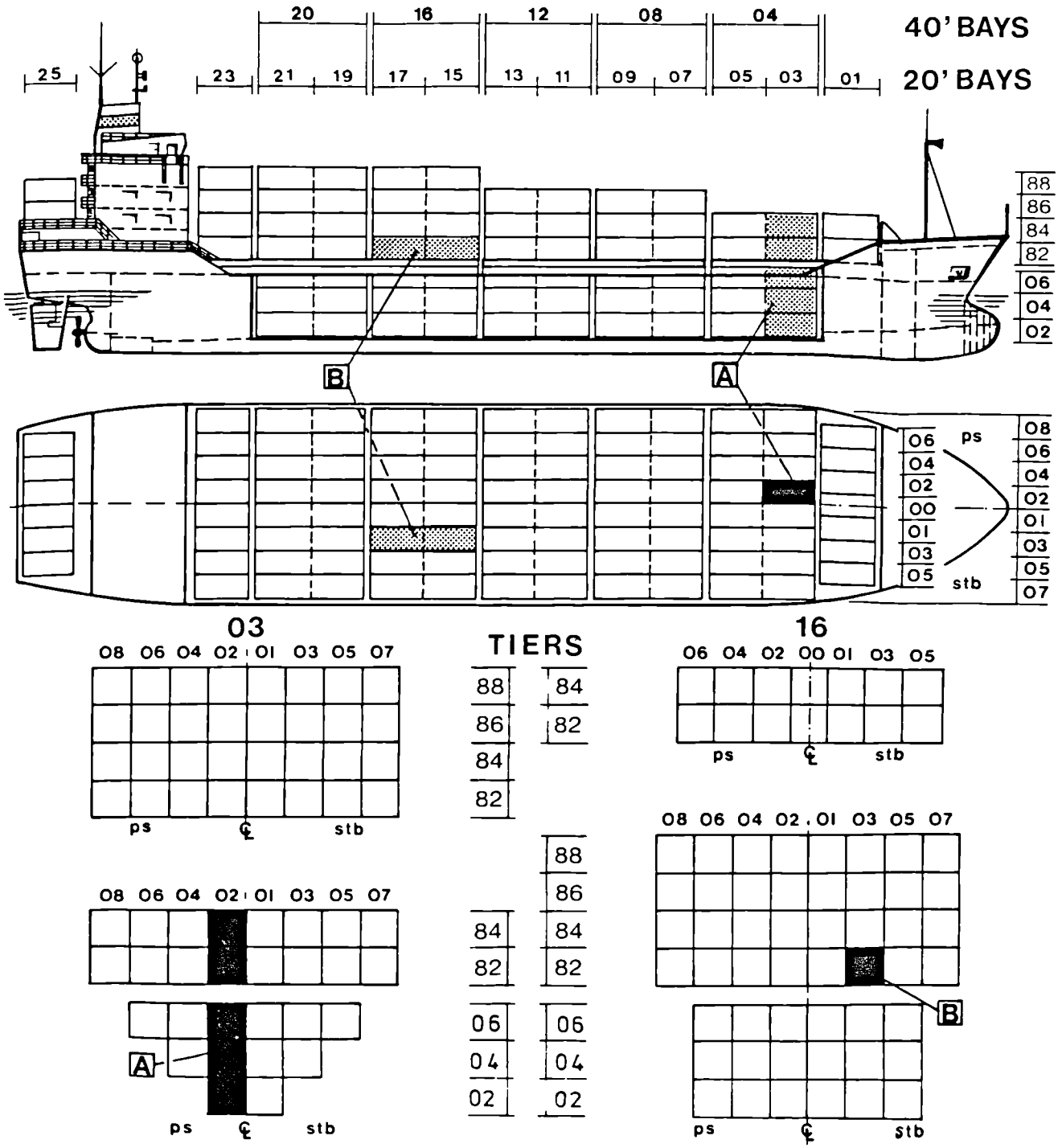


Figure 5.41 Container slot identification schema.

vant container bay identifiers. The transverse distribution of containers can be examined by the user requesting the generation of transverse sections through the ends of particular container bays. A typical output from these procedures is shown in Figure 5.42.

2.5 Determination of tank particulars.

As previously discussed, the carriage of water ballast is an important feature of the containership concept due to the unusual nature of the cargo carried. It is obvious, therefore, that the arrangement of the ballast tanks within a containership hullform is one of the most important aspects of the whole design process. The importance of this activity was recognised during the development of the ship design system, and as such, a part of the containership knowledge base was specifically developed to consider this aspect of design proposal development. This particular area of the knowledge base comprises a combination of heuristic based production rules and external analysis routines which together are able to determine the best arrangement of ballast and other tanks which can be accommodated within the existing vessel arrangement.

The generation of the arrangement of internal tanks is considered in two separate stages by the design system, the first concerning the double bottom region, and the second concerning the side tanks in the cargo region.

2.5.1 Double bottom tanks.

The number of individual tanks contained in the double bottom region of a design proposal, together with their size and location, is dependent upon a number of factors, such as whether or not a duct keel is to be incorporated, or a pipe-tunnel type of arrangement is required. The incorporation of either one of these features will determine the number of watertight/oiltight double bottom girders to be fitted and hence the number of individual tanks to be accommodated. An examination of a number of existing double bottom arrangements on containerships revealed that a number of general configurations were repeatedly used in the arrangement of double bottom regions, with these configurations being shown in Figure 5.43. It should be noted, however, that the arrangements shown only incorporate the watertight/oiltight structure, as these items form the boundaries of the double bottom tanks, and that the other girders and supporting structure needed to support the container stack

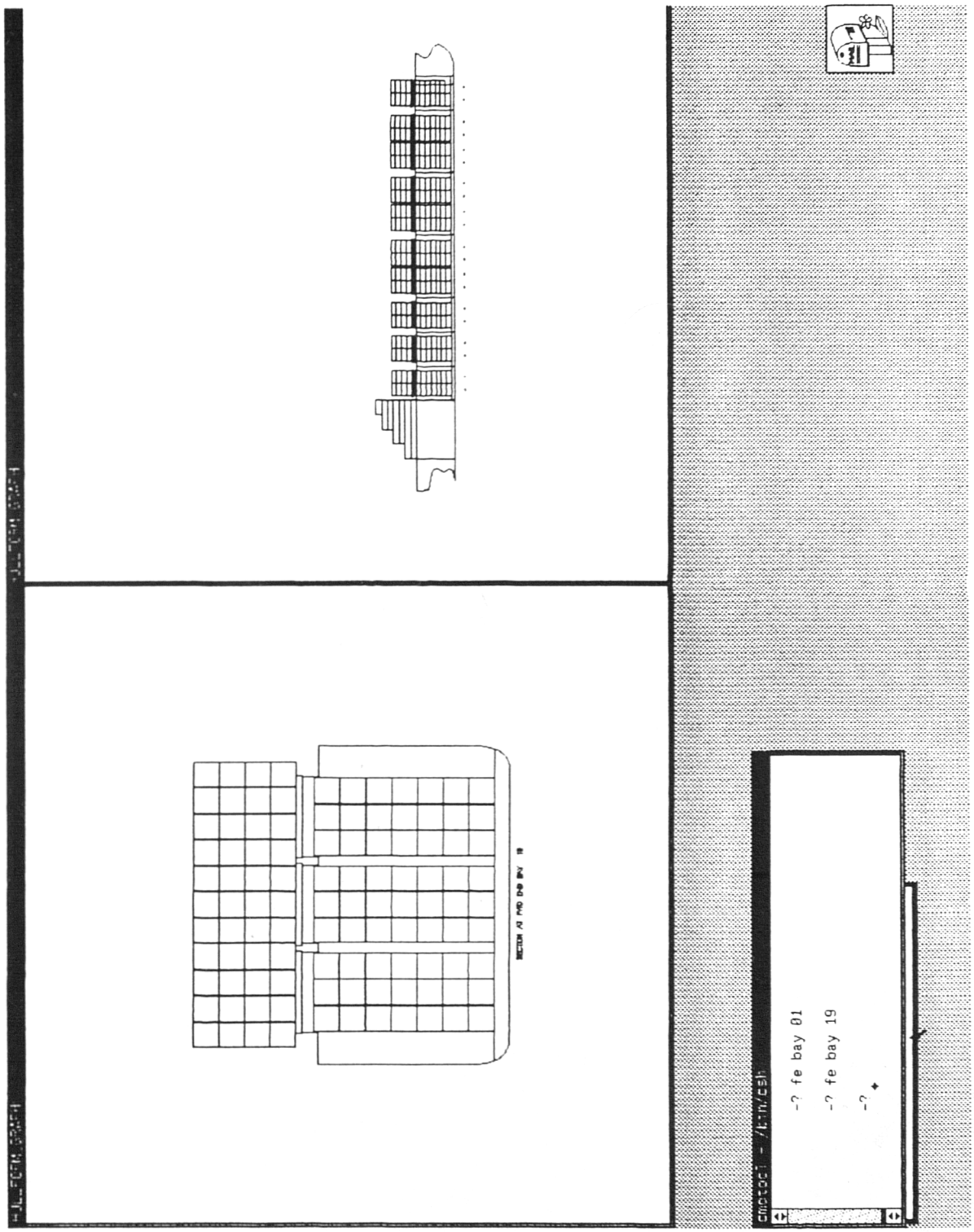


Figure 5.42 Profile and section of a typical containership proposal produced by the system.

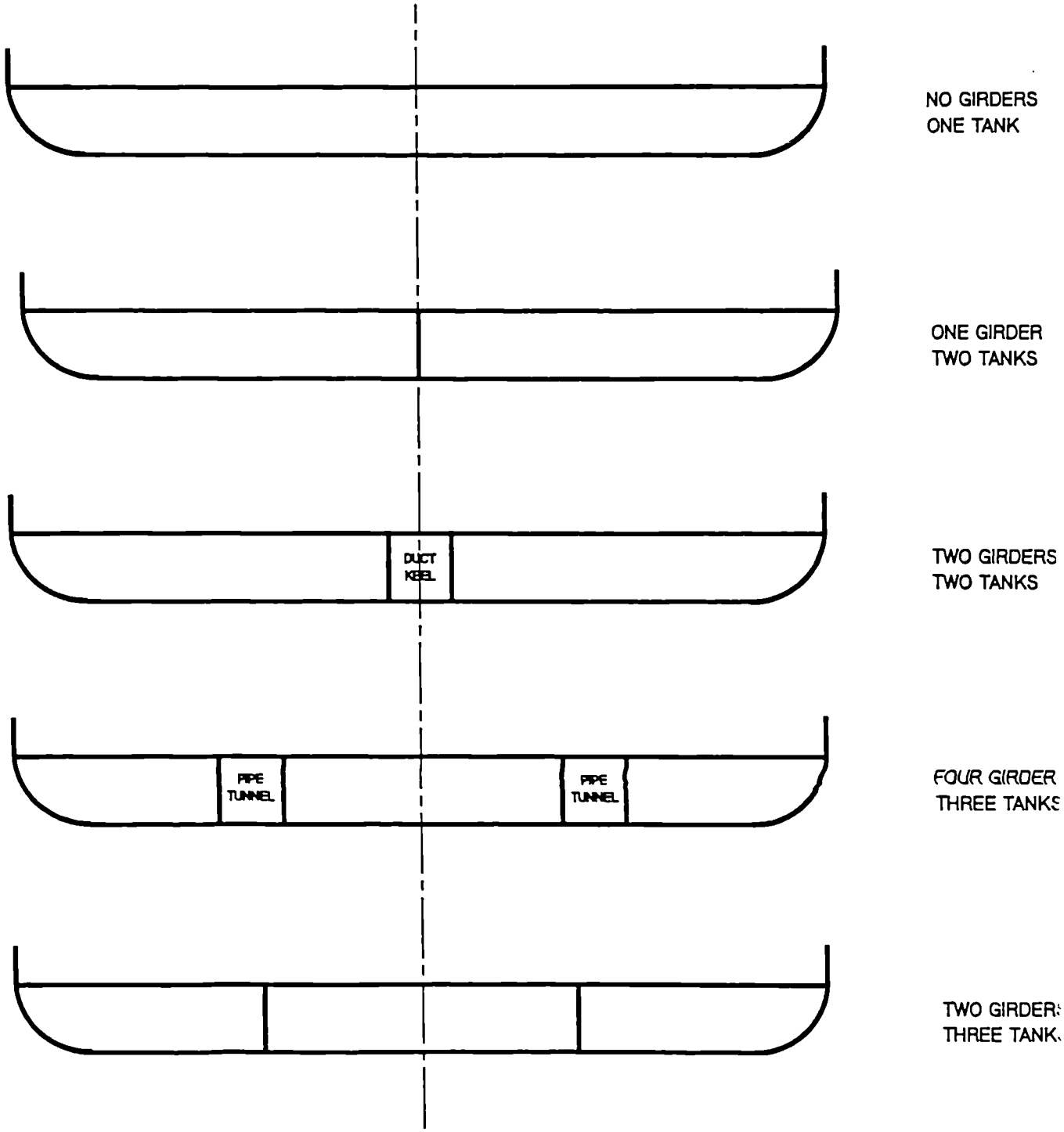


Figure 5.43 Possible arrangements of double bottom tanks.

loads are not considered.

The complete double bottom region of a design proposal is considered by the system as being divided longitudinally into a number of sub-regions, with their fore and aft boundaries corresponding to the fore and aft boundaries of the cargo holds. A decision was made to permit the double bottom schema to be different in each of these sub-regions, as is often the case in practice, to allow, for example, for situations where a double pipe-tunnel arrangement in the main double bottom region was modified to a single duct keel or centreline girder at the forward or aft ends of the vessel. Depending on which of the available configurations is being considered, a number of basic assumptions are made regarding the location of the structural items involved. If a duct keel arrangement is required then this simply involves locating a girder on each side of the vessel at a distance half the width of the duct keel from the centreline, with the assumption being made by the system that the width of a duct keel is equal to 2.0 metres. The specification of a pipe-tunnel based arrangement will result in the generation of two girders on each side of the vessel (assuming that a pipe tunnel is to be installed on both the port and starboard sides of the vessel), with these being separated by a distance equal to the width of the pipe tunnel, which in the case of the design system is assumed to be equal to 1.0 metre. The actual location of the pipe tunnel in the double bottom can only be determined by consideration of the shape of the tank top in the region of the pipe tunnel, as obviously the ends of the tunnel will have to be kept a minimum distance from the tank top/side shell intersection as indicated in Figure 5.44. Maintaining the minimum distance requires that segments of pipe tunnel in adjacent double bottom sub-regions are considered as one continuous structure with the location of the ends of this single structure being checked for violation of the specified minimum clearance requirement. Provided that the minimum clearance is not violated, the pipe tunnel is assumed to be located at a distance of B/6 from the centreline of the vessel (where B is the moulded breadth of the vessel), as indicated in Figure 5.45. If this position would involve violating the clearance requirement then the tunnel structure will be located as far outboard as possible whilst maintaining the clearance.

The above clearance criterion also applies if a single girder is to be located off the vessel centreline in order to give a three tank arrangement, with the girder being located at a maximum of B/6 from the centreline, as shown in Figure 5.46. The final arrangement involving the location of girders is the single centreline girder, which

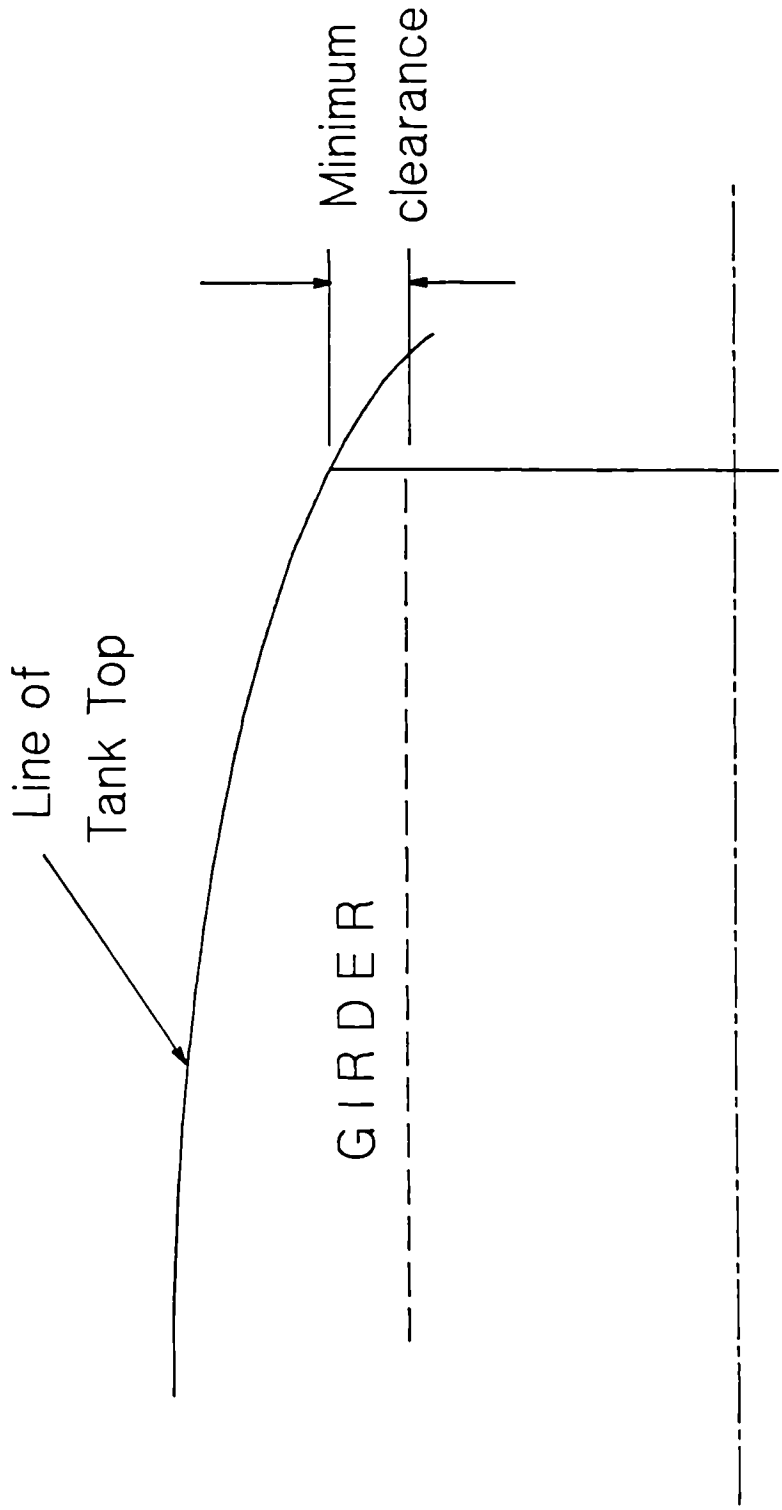


Figure 5.44 Required clearance between double bottom girders and the side shell.

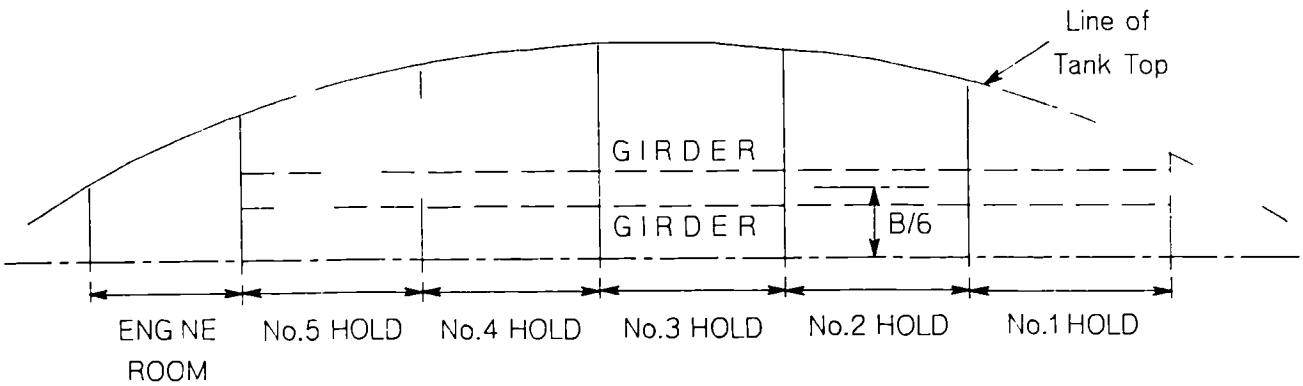


Figure 5.45 Location of a double bottom pipe tunnel.

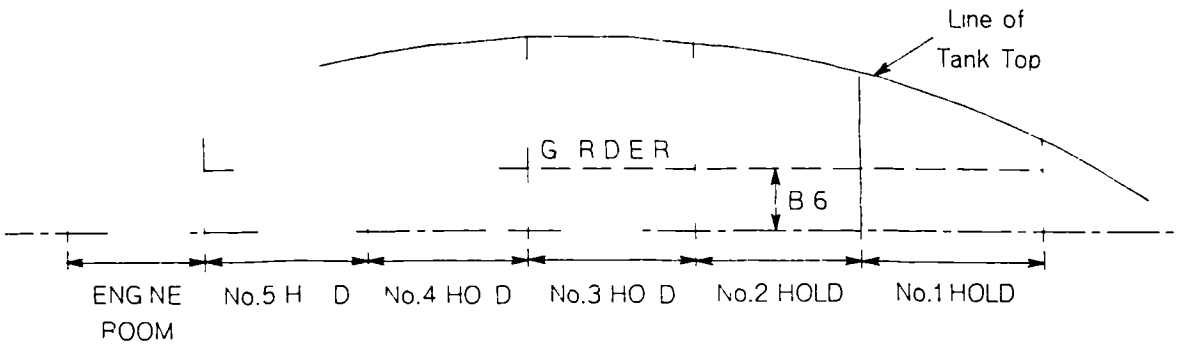


Figure 5.46 Location of a double bottom side girder.

results in the creation of a simple twin-tank arrangement.

Assuming that the location of the various double bottom girders has been decided upon, the next stage is to determine the information required in order to produce a geometric definition of the tanks. The technique developed to perform this task is based upon a *portion* definition of the tank geometry, with individual portions being grouped together to form complete tank descriptions. A single portion is defined by three offsets at each of three transverse sections, as illustrated in Figure 5.47, with the offsets of the portion being measured from the centreline of the vessel. By assuming that any portion can be located on either side of the vessel, and that it can be negative (representing a void space), any number of individual portions can be combined to provide a full description of individual tanks or compartments. As the properties of the separate portions, such as volume, waterplane area, centroid location, free surface moment etc., can easily be determined, the same particulars for the complete tank can be produced by means of a simple summation of the relevant individual portion particulars.

The required portion offsets are determined in a number of different ways depending on whether the portion extends to the side of the vessel or terminates at some point inboard of the shell. If the portion under consideration extends to the side of the vessel then the relevant offsets are determined by interpolation of a cubic spline representation of the hullform definition. Portions which are terminated before reaching the side of the vessel, by a girder for example, will have offsets which are simply derived from an examination of the structure which causes their termination. An example of the above circumstances is shown in Figure 5.48 which illustrates the way in which portion data is used to define tanks created by the insertion of a pipe tunnel as described earlier.

From the above description of the technique adopted for the generation of tank particulars, it is obvious that the height and length of the individual portions which comprise a tank description will have an effect on the accuracy of the resulting calculations of the associated geometric properties. It was therefore decided that each tank would be made up of ten portions along its length in order to give sufficient definition for the calculation of the associated properties. It can also be appreciated that such a high definition is only required when the compartment under consideration is bounded by the side shell of the vessel, and that for rectangular or trapezoidal

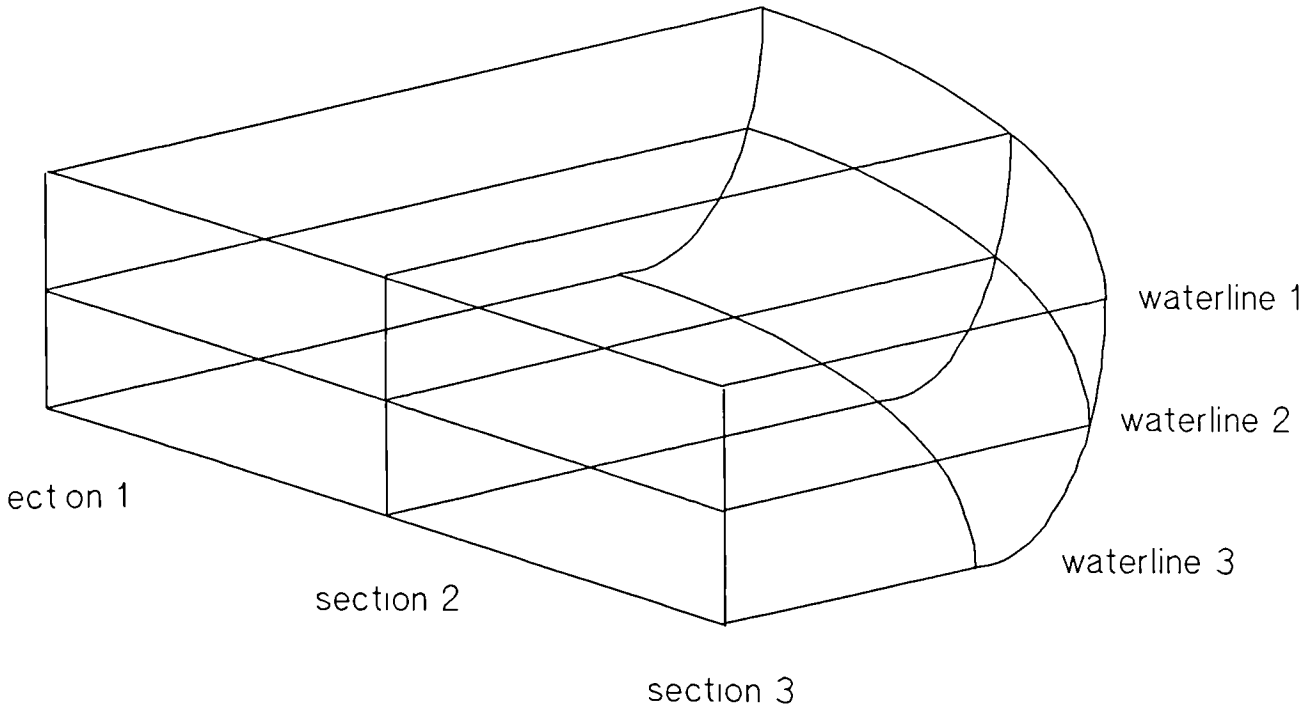


Figure 5.47 Definition of a portion for tank capacities calculation.

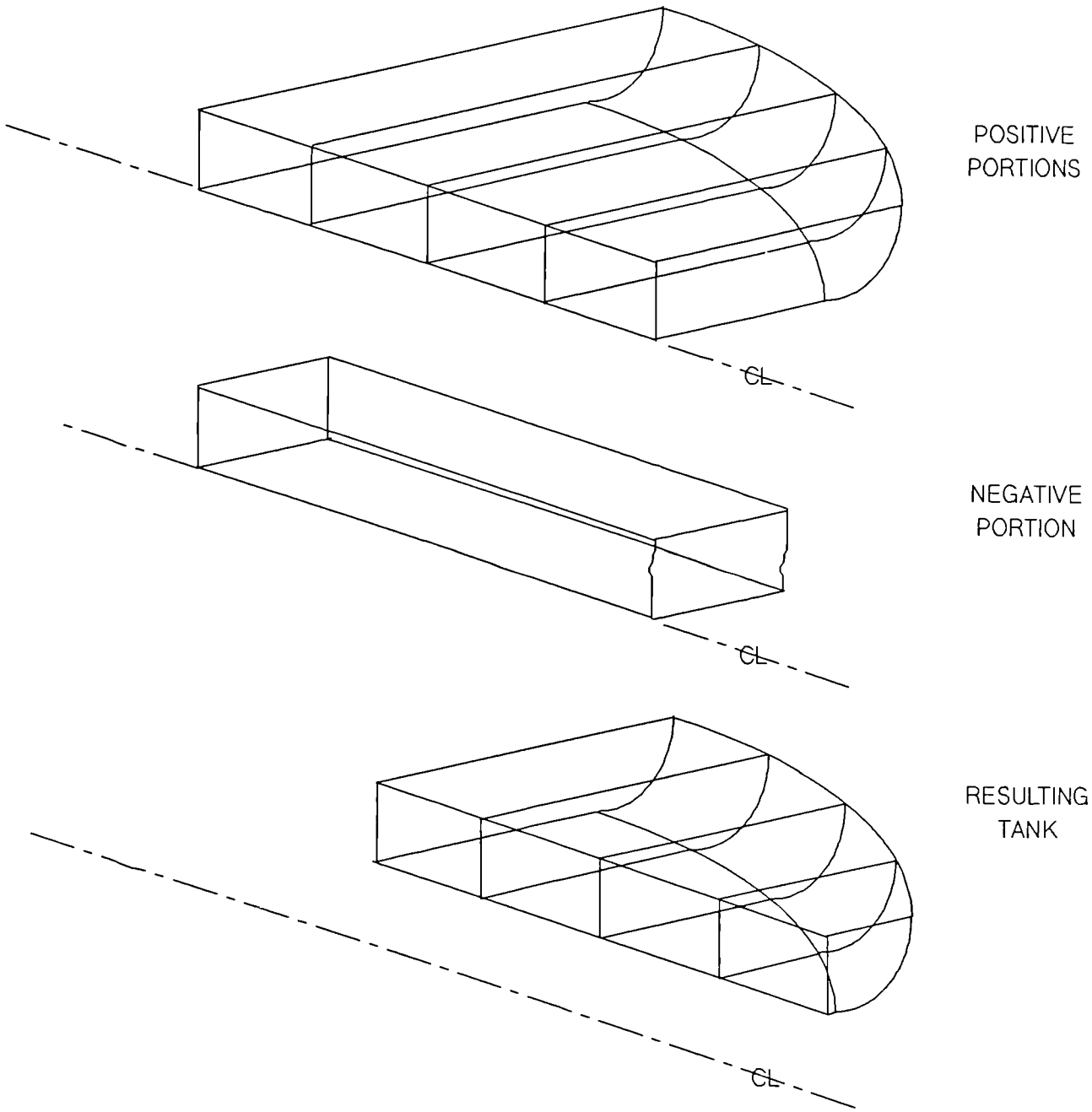


Figure 5.48 Using portions to define tank geometry.

tanks, a single portion definition could be used and still obtain absolute accuracy in terms of the calculation of geometric properties.

The system, in its present form, initially assumes that the double bottom region of a design proposal contains only a duct keel structure with the result that two double bottom tanks are created in each of the defined cargo holds. The system automatically identifies these tanks and assigns identifying labels to them, after which the portion description data is generated from which the associated geometric properties are determined. These property particulars are stored in the database in a form suitable for further use by the system and also for examination by the system user, as illustrated in Figure 5.49.

2.5.2 Side tank arrangement.

The fact that containerised cargo can only be stowed on board a vessel within the line of the hatch openings results in the creation of spaces outboard of the hatches which can conveniently be used for the creation of tank spaces. The uniform nature of the cargo unit also results in the creation of spaces at the ends of the vessel which are suitable for use as tankage. The need for containerships to carry considerable amounts of water ballast means that these side tank spaces will often be used to provide additional ballast capacity even though their relatively high centroids makes them less efficient in terms of their effect on the overall vertical centroid of the vessel. Such tanks are better used for the carriage of fuel oil as this is a consumable item and as such will be used during a voyage with the result that the overall vessel vertical centroid will be reduced. The carriage of fuel oil inside tanks, as opposed to the normal practice of using double bottom spaces, is also beneficial in respect of free-surface effects caused by fuel tanks being partially filled, as the moments of inertia of these tanks are much lower than those of double bottom tanks of the equivalent volume. It is also beneficial with respect to pumping and stripping operations.

When attempting to determine the arrangement of side tanks which can be accommodated in a vessel, the design system works on the basic assumption that all of the available spaces outboard of the overall container block are available to be used as tanks. It is further assumed that the side spaces are divided into individual tanks along the length of the vessel with their boundaries corresponding to the boundaries of the defined cargo holds. The vertical limits of the tanks are defined by the tank top

NO. 1 D.B. TANK (PORT)
WATER BALLAST

FLUID DENSITY : 1.025 Tonnes/cu.m.
STRUCTURAL ALLOWANCE : 2.0%

DEPTH (m)	MASS (t)	AREA (m2)	LCG (m)	VCG (m)	TCG (m)	FSM (m4)
0.07	3.2	50.0	181.193	0.036	2.849	527.2
0.14	7.0	57.5	181.370	0.074	2.954	693.2
0.21	11.3	64.3	181.511	0.112	3.059	870.0
0.28	16.0	70.2	181.627	0.152	3.160	1050.5
0.35	21.2	75.4	181.723	0.191	3.255	1227.1
0.42	26.6	79.8	181.802	0.231	3.344	1392.5
0.49	32.4	83.5	181.868	0.271	3.426	1539.9
0.56	38.3	86.3	181.924	0.311	3.499	1663.1
0.63	44.5	88.4	181.971	0.350	3.565	1757.1
0.70	50.8	89.8	182.010	0.389	3.622	1818.0
0.77	57.2	92.1	182.044	0.428	3.671	1928.8
0.84	63.7	94.3	182.075	0.466	3.717	2037.1
0.91	70.4	96.4	182.103	0.505	3.762	2142.0
0.98	77.3	98.3	182.129	0.544	3.804	2242.9
1.05	84.2	100.1	182.153	0.583	3.845	2339.2
1.12	91.3	101.7	182.176	0.622	3.883	2430.2
1.19	98.5	103.2	182.196	0.661	3.920	2515.3
1.26	105.8	104.6	182.215	0.700	3.955	2594.0
1.33	113.2	105.8	182.233	0.739	3.988	2665.8
1.40	120.5	106.9	182.250	0.777	4.018	2728.6

Figure 5.49 Example of geometric particulars of a double bottom tank as produced by the system.

at the lower limit and by the second deck at the top of the tank. In the mid-region of the vessel, where the distribution of containers is not affected by the shape of the vessel, the side tanks are assumed to extend from the line of the hatch side girder, outboard to the side of the vessel as indicated in Figure 5.50.

It was noted during the knowledge elicitation sessions that there is a tendency to subdivide side tanks on containerships into upper and lower tanks as shown in Figure 5.51, with the lower tanks being used for fuel oil and the upper ones being utilised as ballast tanks. It was also discovered that this approach was adopted as a result of experience gained when operating container vessels with these vessels sustaining damage to their side structure when berthing. The repair of such damage tended to be a highly laborious process when the involved structure was part of a side tank used for the carriage of fuel oil. The adoption of a split tank arrangement, with the fuel tanks being below quay level and therefore clear of any damaged areas, results in a much simpler repair operation as the affected tanks will contain nothing more innocuous than sea-water, with there being no need for the careful stripping of the tanks before the repair work can commence. With this arrangement, the risk of pollution occurring as the result of an accident is also considerably reduced, a fact which is considered to be important in view of present environmental concerns. The ability to incorporate a split side-tank arrangement is also provided in the regions towards the ends of the vessel, away from the midship region. In these regions the arrangement of the container cargo is affected by the shape of the hullform, with this effect being reflected by the shape of the associated side tanks. As well as providing tank space, the enclosed side spaces in these regions also perform the function of providing platforms to support the associated containers. The nature of the arrangement of these containers results in the side tank configuration being stepped in both the horizontal and vertical directions in order to follow the shape of the container block, as shown in Figure 5.52.

In order that the geometric particulars of these tanks can be determined, the design system adopts a portion description approach similar to that used in the investigation of the double bottom tank particulars described previously. This time, the approach involves the generation of portion data which describes the complete hullform in the particular region under consideration, with negative portions being generated corresponding to the locations of the outboard containers. The superposition of these individual positive portions, and the relevant negative portions, results in the tank

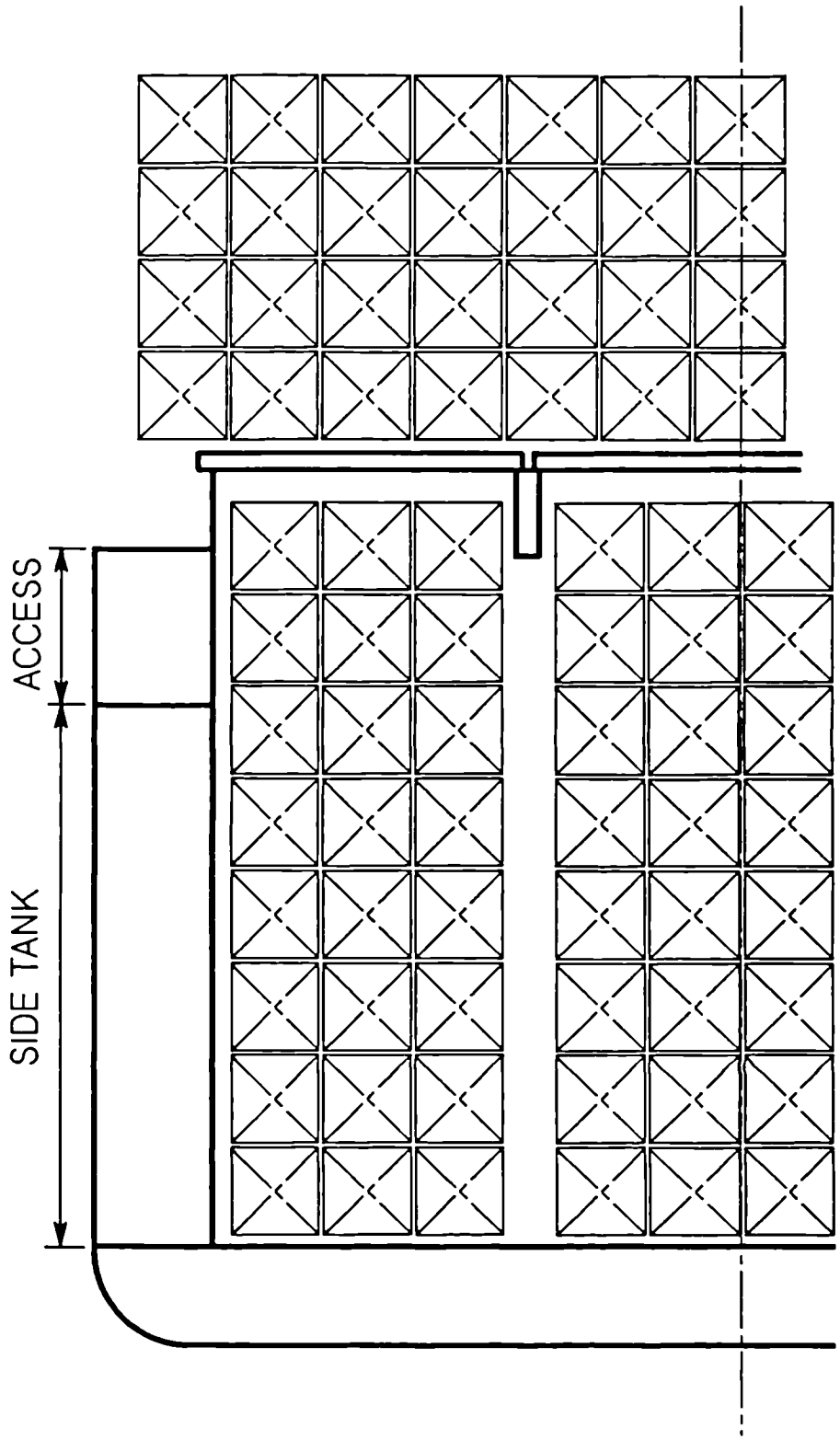


Figure 5.50 Side tank arrangement in midship region.

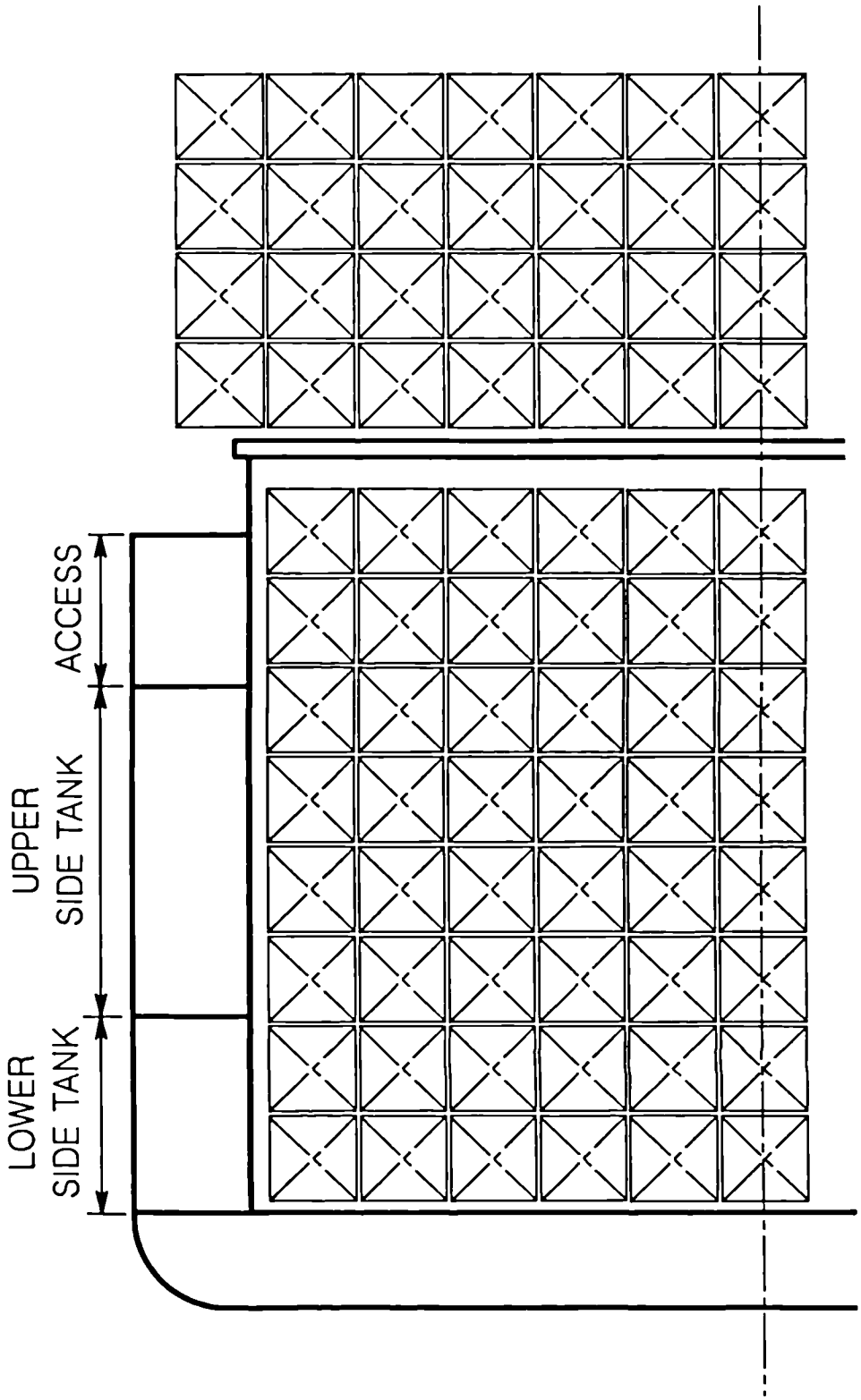


Figure 5.51 Division of side tanks into upper and lower compartments.

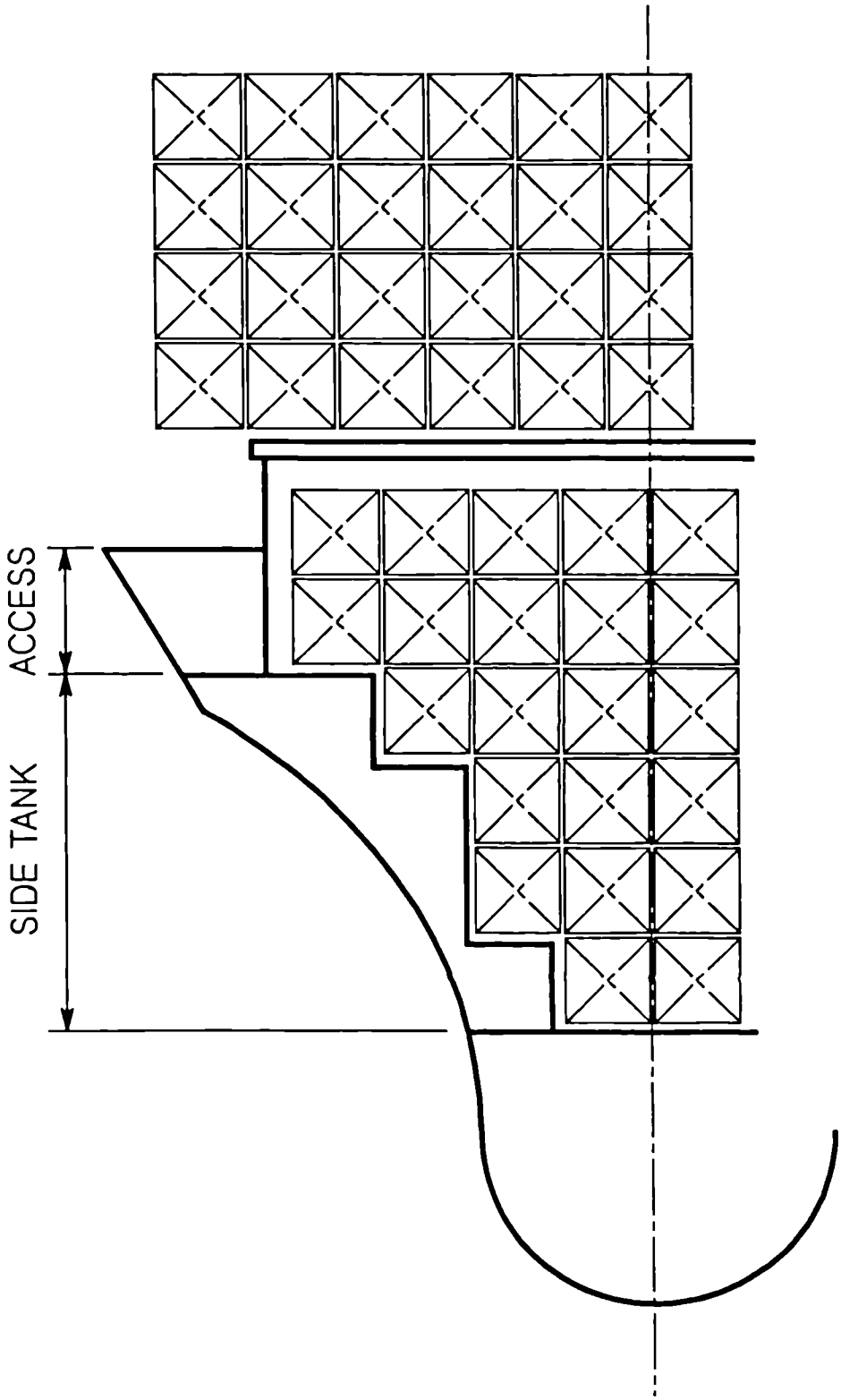


Figure 5.52 Stepped side tank at the forward end of a vessel.

geometry being defined by the remaining shape.

Once each of the tanks which can be accommodated has been defined, the system automatically assigns on identifying label and then calculates the relevant geometric particulars. These particulars are stored in the system database in a format which is suitable for further use within the system and also for examination by the user, as shown in Figure 5.53.

2.5.3 Determination of tank particulars.

The method utilised for calculating tank particulars is based upon the systematic examination of the relevant portion descriptions and the summation of their individual properties to produce the particulars of the complete tank. As the technique is based upon the consideration of portions on an individual basis, an explanation of the calculation process involved can therefore be achieved by consideration of a single portion description. The properties of a portion are determined basically by two-way integration of the relevant portion offset data, firstly in the vertical plane to determine sectional areas, then horizontally to provide volumes and the properties of volume. The integration is performed using Simpson's first rule for equally spaced ordinates. If the available ordinates are not equally spaced, the three available ordinates are used to interpolate an intermediate one using the Lagrange three point interpolation technique. Once the sectional area and area properties have been determined at each of the three sections, the Lagrange interpolation scheme is also used to generate an intermediate section description so that the sectional data can be integrated to produce volume related information.

The properties which have to be calculated for each of the relevant portions is dependent upon its location within the tank in relation to the current sounding depth. For example, those portions which are completely below the level being considered will only contribute to the volume and centroid properties, whereas those portions which straddle the level under consideration will also contribute to the free surface moments of the tank. Summation of the properties of all the relevant portions, with account being taken of the status of the portion in terms of it being positive or negative (representing a void) and also its position in the vessel (port or starboard side), at each of the required sounding depths, will result in the production of the complete tank particulars as previously illustrated in Figures 5.49 and 5.53.

NO. 2 HOLD SIDE TANK (P)
WATER BALLAST

FLUID DENSITY : 1.025 Tonnes/cu.m.
STRUCTURAL ALLOWANCE : 2.0%

DEPTH (m)	MASS (t)	AREA (m2)	LCG (m)	VCG (m)	TCG (m)	FSM (m4)
0.72	203.0	288.7	164.593	1.765	6.805	18414.0
1.44	417.7	302.4	164.633	2.135	6.967	20713.6
2.17	712.5	414.6	164.327	2.580	6.906	26346.8
2.89	1016.1	422.1	164.207	2.983	6.916	27726.4
3.61	1324.4	427.8	164.151	3.371	6.945	28812.7
4.33	1633.2	432.1	164.122	3.749	6.981	29645.8
5.05	1947.9	435.5	164.106	4.128	7.013	30302.9
5.78	2264.6	437.8	164.097	4.504	7.042	30770.3
6.50	2579.7	439.6	164.093	4.874	7.070	31122.0
7.22	2899.0	440.9	164.091	5.247	7.093	31387.5
7.94	3219.2	442.1	164.090	5.618	7.114	31637.6
8.66	3540.2	443.2	164.090	5.989	7.132	31856.8
9.39	3858.9	444.2	164.092	6.355	7.150	32046.0
10.11	4181.4	445.2	164.094	6.725	7.165	32243.4
10.83	4504.7	446.3	164.098	7.094	7.179	32461.2
11.55	4825.7	447.6	164.102	7.459	7.194	32708.4
12.27	5150.8	448.9	164.107	7.829	7.207	32974.0
13.00	5476.9	450.3	164.113	8.198	7.220	33262.3
13.72	5804.1	451.9	164.119	8.568	7.232	33582.8
14.44	6128.5	453.7	164.127	8.934	7.245	33935.3

Figure 5.53 Example of geometric particulars of a side tank as produced by the system.

The availability of such detailed information regarding the distribution and geometric properties of the available tank spaces may appear, at first sight, to be rather unnecessary in view of the fact that only the concept stage of containership design is being considered and such a high level of definition may not be absolutely necessary at this stage. The decision to utilise the ability of the system to produce such detailed information was made as a result of the great importance attached to ballast water as a parameter in the design of containerships, a fact not reflected by some other containership design systems, as mentioned previously. The way in which the available tank information is used by the system will be discussed in some detail later.

2.6 Interactive compartment definition.

When considering the creation of the general arrangement of the vessel it was mentioned that as well as the knowledge based procedures for the automatic generation of proposed layouts, a means was provided for the interactive definition of an arrangement by the system user. The available interactive layout definition procedures were described in some detail in Section 2.3.5. In view of the interactive layout definition capability incorporated into the system, a decision was made to provide the system user with the option to use interactive compartment definition procedures to define internal compartments in preference to the automatic generation of compartment particulars described above. The provision of user-driven compartmentation routines was considered to be of considerable benefit to the overall flexibility of the system, due to the ship-type independent nature of such interactive compartment definition procedures resulting in the ability to use them for the definition of compartment particulars for a wide range of vessel types. A description of the methodology adopted to form the basis of the interactive compartmentation procedure is given in the following sections.

Within the design system being described here, the process of interactive compartment definition is considered to be distinct from that of interactive layout definition. The definition of any internal arrangement will obviously result in the creation of enclosed spaces, and it is the process of the systematic identification of these enclosed spaces which is termed compartment definition. Within a system which is intended for use in concept design investigations, there is obviously the requirement that the compartment arrangement can be defined as quickly as possible and the particulars of those compartments determined so that the quality of the proposed arrangement

can be easily assessed. This is of particular importance in the development of proposals for deadweight limited vessels where the acceptability of a design is judged primarily against its ability to provide sufficient volume for the carriage of the required cargo mass.

2.6.1 Relational data handling.

The development of an interactive compartmentation procedure which was based upon the use of a purely geometric description of compartment particulars, would present the user with considerable difficulties if it was required to change some feature of a defined layout. For example, if the position of a bulkhead or deck was to be changed, then this would require the definition of all of the compartments affected by this change to be modified to reflect the revised layout. This approach is quite unacceptable in a system intended for use at the concept design stage where many modifications to any proposed layout could be anticipated, as this would put considerable responsibility on the user to ensure that the compartment definition was kept up to date and that the compartment particulars reflected the current state of the defined internal layout.

In order to overcome the problems described above, a decision was made to develop the interactive compartment definition procedure based upon a compartment description which used the relationships between the various layout boundary elements to define the compartment particulars. As a result of utilising relationships between boundary elements to define compartments, the actual physical location of these elements is of no importance to the actual compartment description as the location and extent of the boundaries are only considered when it is required to calculate the geometric properties of the defined compartments. Thus, the components of the layout, the decks, bulkheads etc, can be modified without affecting the current compartment definition, with the modifications only having an effect when the geometric properties of the affected compartments are re-evaluated. The adoption of this approach has resulted in the development of a relational data handling technique which is considered to be unique to the system.

The technique developed for handling the data associated with the definition of the individual components of the internal layout model and the compartment definition particulars was required to overcome two major problems:

- the different boundary element types required different descriptive data,

- the inherent physical relationships between individual boundaries (topology) had to be represented.

The basic scheme of the relational data handling method developed for inclusion in the system is shown diagrammatically in Figure 5.54. The technique can be seen to utilise three basic elements:

- boundary definition file (index system),
- element files (boundary geometry data),
- compartment definition file.

2.6.1.1 Boundary definition file.

This part of the data handling technique can be considered as the main indexing procedure for the interactive layout definition routines described earlier. The file consists of three basic parameter groups which together form the layout element index and boundary relationship indicator. During the definition of a proposed internal layout by the system user using one of the interactive methods provided, this index file is constantly updated to provide an accurate record of the current state of the development. Each of the defined boundary elements is automatically assigned a unique numerical identifier upon its creation by the system user, with this identifier being used as the main reference for all of the subsequent boundary relationship evaluations and compartment definitions. In addition, the type of each element created is noted and stored in the index file, together with an identifier which records the position of the element within the boundary type sub-set.

2.6.1.2 Element files.

Each of the available boundary types, as described previously, has an element sub-set file which is structured to accommodate the data required to describe the geometry of that particular type of boundary. The individual boundaries within the sub-sets are assigned local identifiers which correspond to the type-specific identifiers contained in the boundary definition file described above. Thus the particulars of any boundary element within a defined layout can be determined from knowledge of its unique boundary identifier (as this allows its type to be determined together with its type sub-

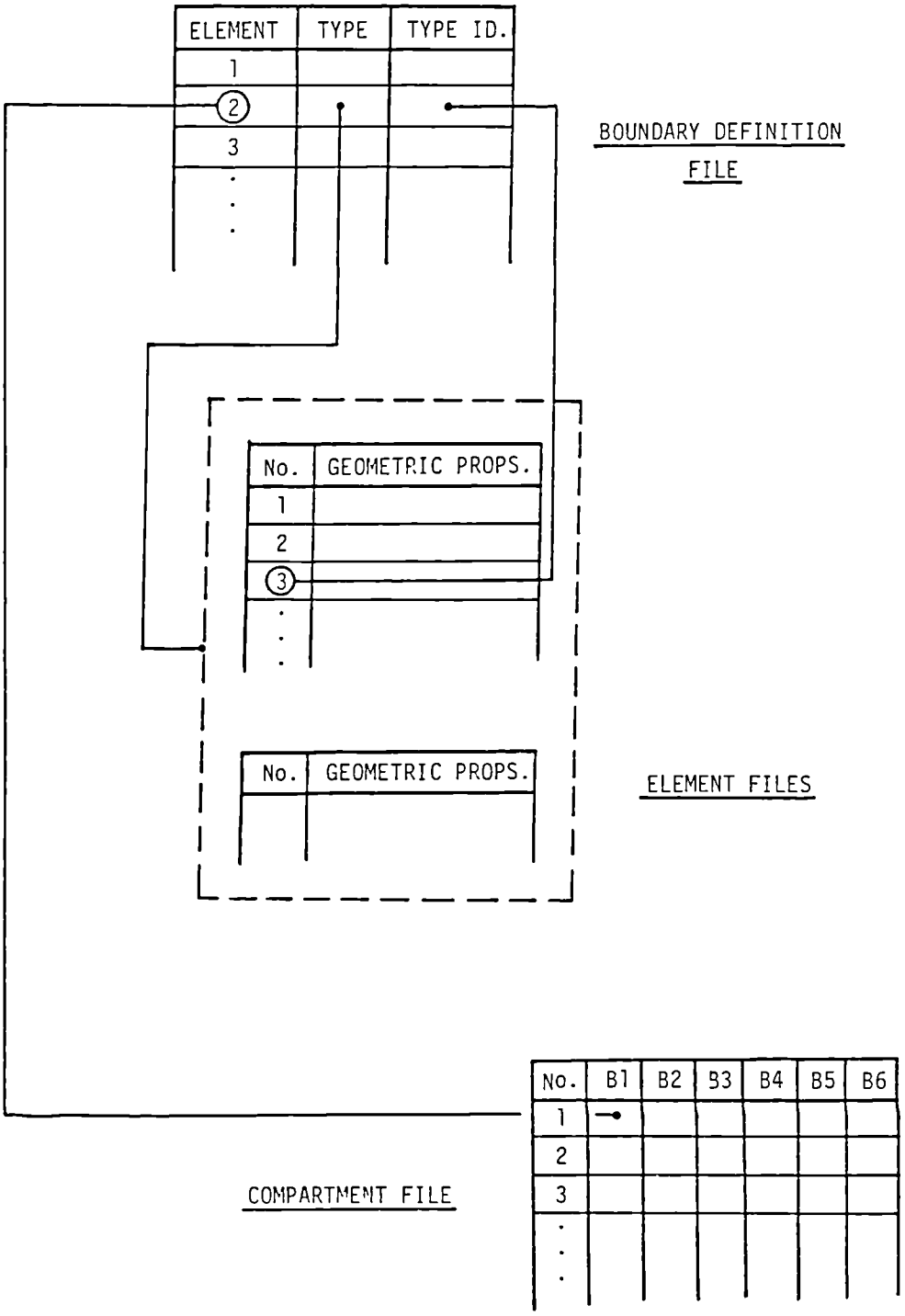


Figure 5.54 Relational data handling in the interactive compartment definition procedure.

set identifier) from which the geometric particulars of the boundary can be obtained from the relevant element file.

2.6.1.3 Compartment definition file.

For each compartment defined by the user, a record is created in the compartment definition file to accommodate the identifiers of the group of boundary elements which combine to represent the compartment. As this method of defining a compartment does not directly involve details of its size, location etc., modifications can be made to the geometric definition of the boundary elements, as mentioned earlier, without having any effect on the compartment description.

Before the system can create the compartment definition record, the boundaries which combine to form the compartment must first be identified. In order to achieve this, the same approach has been adopted for interactive compartment definition as was used in the interactive layout definition procedure, that is, interactive graphics. This enables the system user to rapidly define which of the enclosed spaces in a proposed layout are of interest and determine their associated geometric properties. Presented with a profile of the vessel on the graphics screen, the user has simply to indicate the longitudinal position of the relevant compartment using the digitiser mouse device, and then indicate the transverse location of the compartment on a sectional view which is produced on the graphics screen as a result of the first action. Having completed this process, the user is then asked to supply a compartment identifier and a compartment function label, both of which are used as a means of reference by other modules of the design system. The user is also prompted to supply the relevant factors to allow the conversion from moulded to net particulars to be performed. Having obtained all of the relevant data, the procedure then determines which of the defined boundaries are actually involved in defining the compartment. This is achieved by considering the single point within the compartment which was previously indicated by the user and looking for the boundaries which surround this point. Once the boundaries of the compartment have been identified the relevant record in the compartment definition file is created.

When requested to do so by the user, the compartmentation routines calculate the geometric properties (volume, centroid location, free surface moment) of the defined compartments. It is only at this point that the locations, shapes, etc., of the various boundaries are utilised in order to assess the required compartment particulars, by

means of the data relationships described earlier.

The geometric particulars of the compartments, as calculated by the procedure described above, are presented to the user in textural format for checking as shown in Figure 5.55. The data generated is also used to create sounding diagrams which relate the geometric particulars to height above compartment base, with these sounding diagrams being available to the user, as shown in Figure 5.56. The system will also produce a general arrangement type of drawing which shows the complete defined layout together with the locations of all of the defined compartments. An example of this form of output is shown in Figure 5.57.

An example of the use of the interactive layout and compartmentation procedures in the development of a proposal for a Ro-Ro vessel is given in [5.31], which can be found in Appendix I.

2.7 Investigation of loading conditions.

Having determined the proposed arrangement of compartments, either automatically or on an interactive basis, the next stage in the development of a design proposal is the investigation of the proposed vessel loading conditions to assess their acceptability when measured against the various relevant criteria.

When considering the investigation of loading conditions for containership proposals, the infinite variability of the possible loading patterns must obviously be taken into account. As mentioned in Chapter 4 of this thesis, the containership concept is in a fairly unique situation in terms of the complexity of the loading conditions problem. In the context of the concept design system, it was decided that this problem required an equally unique solution. This involved the development of a series of routines which allow the user to investigate any proposed loading arrangement and assess its acceptability against capacity, draft, stability and economic criteria, and display the results in both tabular and graphical form.

In order to allow the user to define realistic loading arrangements in terms of distributions of container masses, the procedures developed for the investigation of loading conditions use the container slot descriptive data previously generated to access the geometry of the cargo block. The user is able to define conditions by means of a set of commands which allow homogenous, non-homogenous, and tapered loading

No	COMPARTMENT	FUNCTION	AFT END	FWD END (m Fwd AP)	LCG	VCG (m AB)	VOLUME (cu.m)
1	DEEP TANK	WATER BALLAST	121.920	127.635	124.538	5.815	203.0
2	No.1 D.B. TANK	WATER BALLAST	121.920	127.635	125.520	0.889	21.0
3	No.2 D.B. PORT	WATER BALLAST	87.630	121.920	98.230	0.871	145.0
4	No.2 D.B. STBD.	WATER BALLAST	87.630	121.920	98.230	0.871	145.0
5	No.3 D.B. PORT	WATER BALLAST	67.310	87.630	75.769	0.844	138.0
7	No.3 D.B. STBD.	WATER BALLAST	67.310	87.630	75.769	0.844	138.0
16	A.HEELING (P)	WATER BALLAST	41.910	80.010	60.782	5.322	697.0
17	A.HEELING (S)	WATER BALLAST	41.910	80.010	60.782	5.322	697.0
						TOTAL	2184.0

No	COMPARTMENT	FUNCTION	AFT END	FWD END (m Fwd AP)	LCG	VCG (m AB)	VOLUME (cu.m)
6	No.3 D.B. CENTRE	HEAVY OIL	67.310	87.630	77.470	0.750	253.0
						TOTAL	253.0

Figure 5.55 Compartment properties derived from the interactive compartment definition procedure.

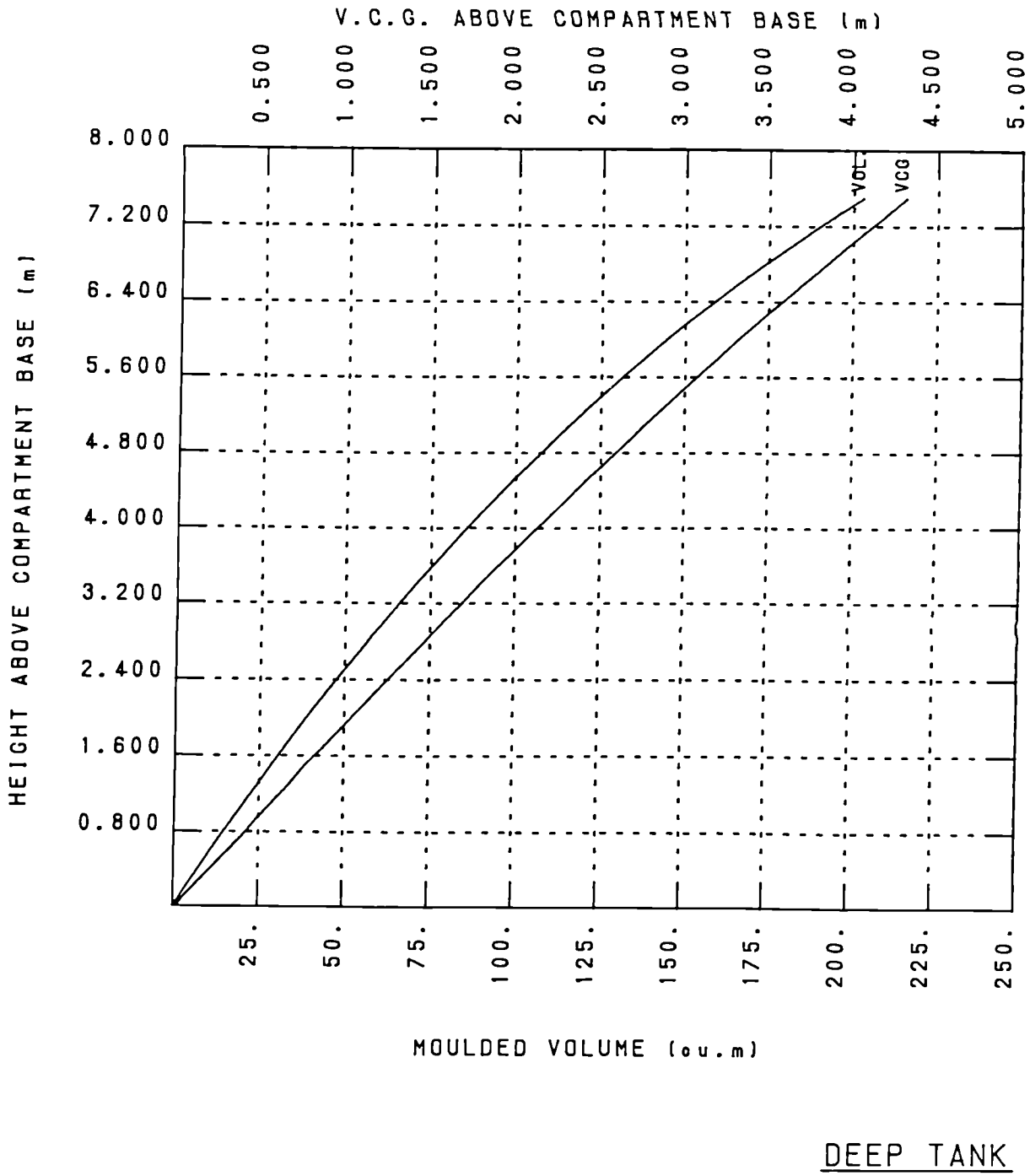


Figure 5.56 Example of a sounding diagram produced by the interactive compartment definition procedure.

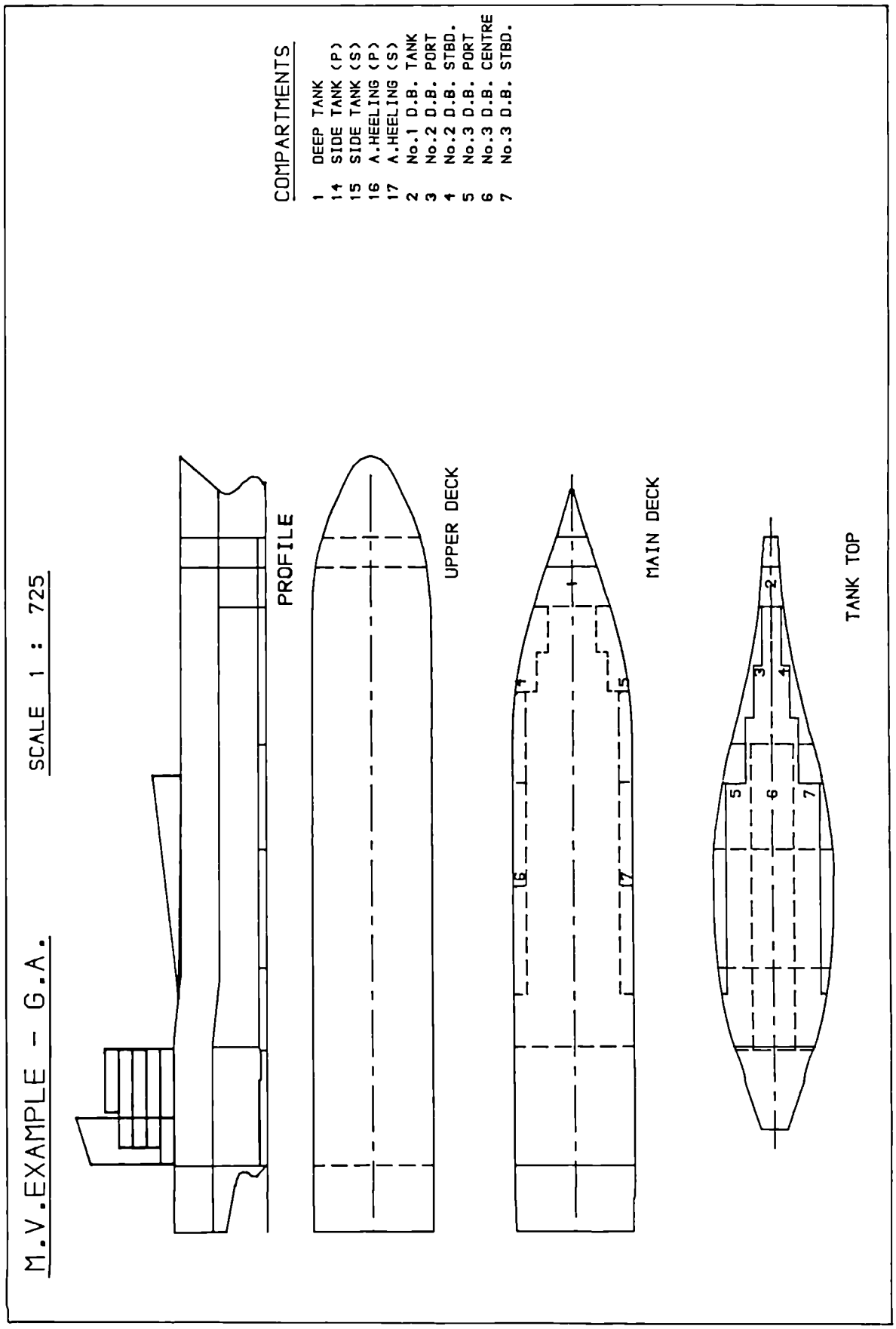


Figure 5.57 General arrangement drawing as produced by the interactive compartment definition procedure.

distributions to be specified. For example, the user can specify conditions where the heavier containers are loaded into the lower tiers with the lighter ones being located in the upper tiers. The user is also provided with the ability to differentiate between the loading in the hold slots and those above deck. Thus the system is able to model conditions which are representative of those which would be encountered in reality unlike present design practice which is generally limited to the investigation of one or two hypothetical uniform conditions.

2.7.1 Limiting criteria.

Regardless of how the containers to be carried on a vessel are loaded, the same basic criteria still have to be satisfied in order for the loading condition to be acceptable. These criteria can be divided into three main groups, as indicated below:

- intact stability requirements,
- geometric limitation,
- economic performance requirements.

The importance of the first class of criteria is quite obvious as any loading condition has to satisfy the requirements of the International Maritime Organisation (I.M.O.) in terms of intact static stability and also intact dynamic stability.

The second group accounts for limitations imposed by the physical characteristics of the design proposal such as the maximum draft (scantling draft) which can be achieved, and also the maximum geometric capacity of the vessel.

The final class of criteria takes account of the operational aspects of the design proposal such as fuel consumption, fuel cost, voyage length, voyage speed, freight rate, and hence vessel profitability. The inclusion of such parameters into the investigation of loading conditions enables a comprehensive picture of the economic feasibility of the proposal to be assessed under various operating scenarios.

2.7.1.1 Intact stability requirements.

As mentioned above, any proposed loading condition is required to satisfy basic stability requirements as specified in [5.32]. In order to determine the stability characteristics of a proposed hullform it is necessary to calculate the cross curves of stability

at a range of vessel drafts and angles of heel. The design system uses an external cross-curve calculation routine developed by the author, to determine the required data, as illustrated in Figure 5.58. Having determined the stability characteristics of the proposed hullform, the next stage in the assessment of intact stability is the generation of maximum vertical centre of gravity values at a range of vessel drafts. The adoption of this approach for the assessment of stability performance, provides for the rapid determination of the suitability of a proposed loading condition. The maximum permissible vertical centres of gravity values at a range of vessel drafts are calculated using a procedure developed by the author. This procedure uses the previously calculated cross curves of stability to determine the maximum total vertical centre of gravity which would satisfy the intact static stability criteria shown in Figure 5.59. An example of the output from this procedure is shown in Figure 5.60.

In addition to the intact statical stability requirements outlined above, containerships are also subject to dynamic stability criteria as shown in Figure 5.61. This is due to the very large above-water lateral area of containerships, caused by a combination of light drafts and large deck cargoes, which results in considerable heeling moments when subjected to wind loadings. A similar approach has been adopted for the treatment of dynamic stability as was used for static stability, that is the determination of maximum permissible values of heeling moments at a range of vessel drafts. This time there is an additional consideration due to the inclusion of the vertical centre of gravity of the vessel in the calculation procedure for wind heeling moments. This requires that the maximum allowable wind heeling moments be determined at a range of assumed vessel centres of gravity values for each of the required vessel drafts, as shown in Figure 5.62.

2.7.1.2 Geometric Limitation.

There are two major limitations on a proposed loading condition imposed bythe geometry of the vessel itself. The first of these is the maximum draft which can be achieved as determined by the value used in the calculation of the hull scantlings. This value of draft will normally correspond to the maximum permissible with respect to freeboard considerations, as previously determined. It should however be noted that this maximum draft will usually not be the same as the design draft of the vessel as the scantlings of the hull will usually be designed to the freeboard draft so as to provide the vessel with additional operational flexibility.

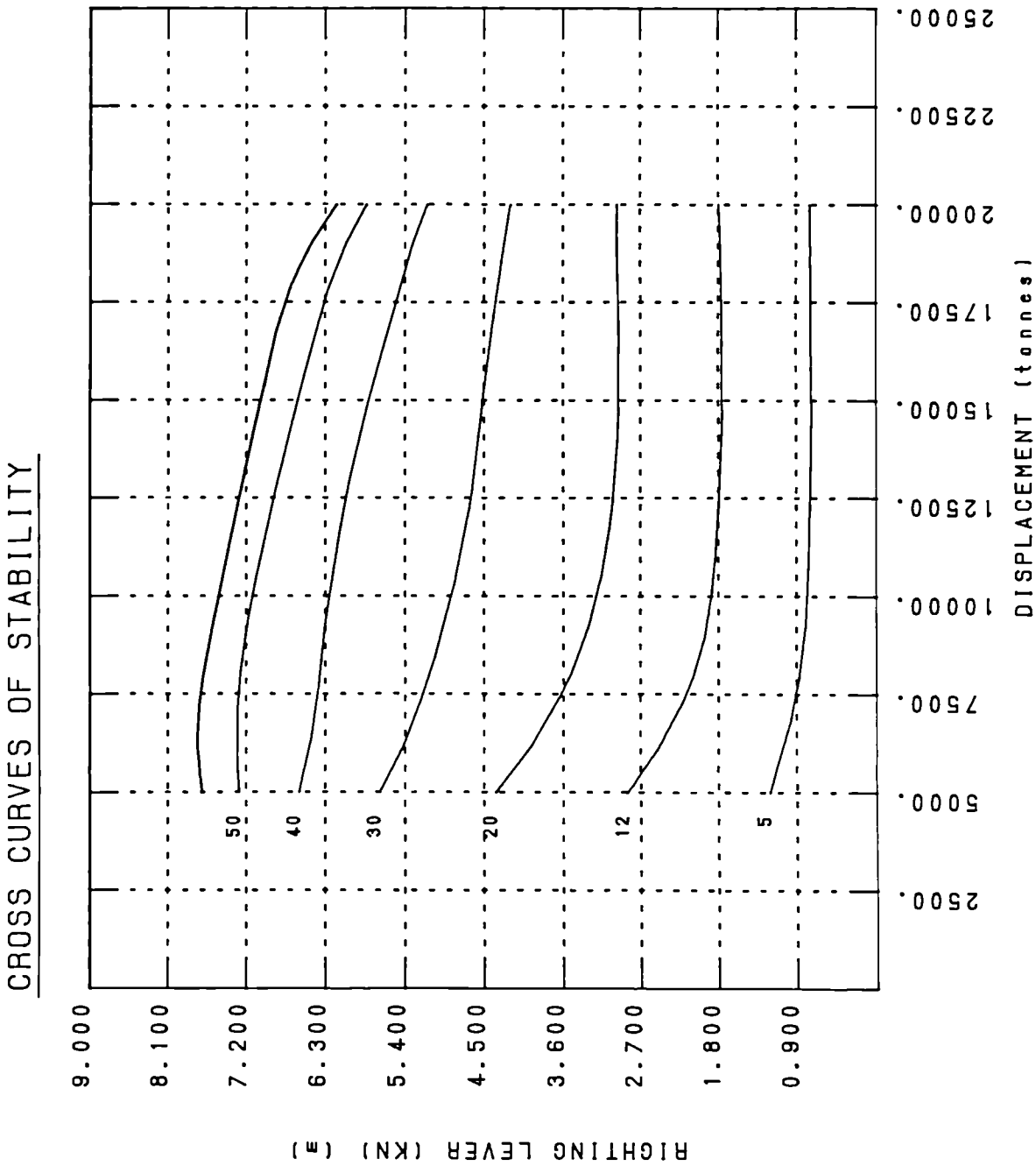
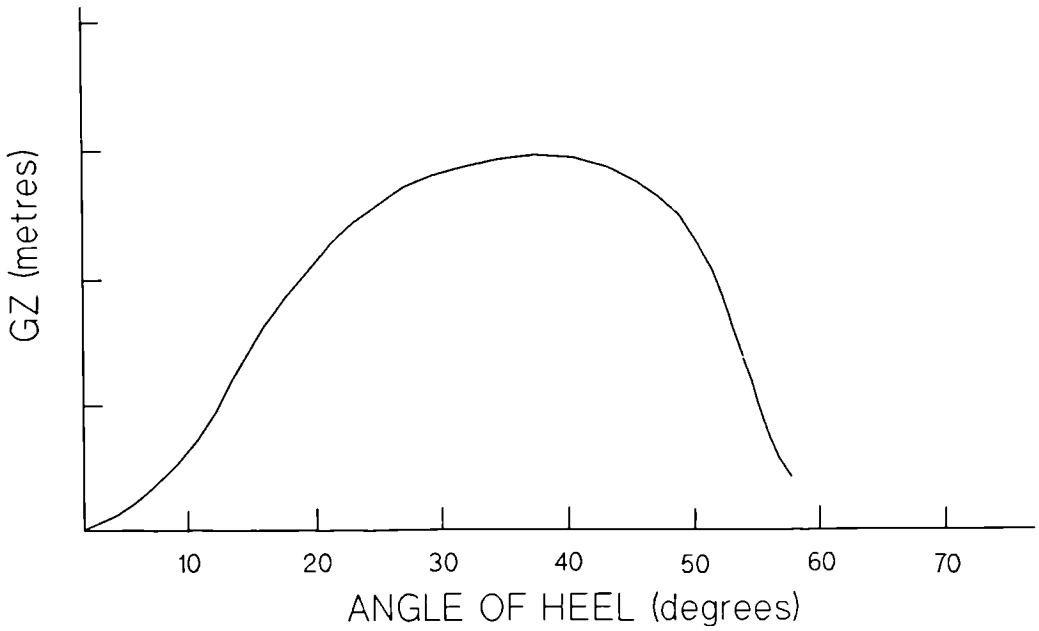


Figure 5.58 Example of graphical output of cross-curve data.



- AREA P TO 30 DEGREES NOT LESS THAN 0.055 m.radians.
- AREA P TO X DEGREES NOT LESS THAN 0.090 m.radians.
- AREA BETWEEN 30 AND X DEGREES NOT LESS THAN 0.030 m.radians.
- X S ANGLE F DOWNFLOOD NG OR 40 WHICHEVER IS LEAST
- MAX M M GZ TO OCC R AT ANGLE NOT LESS THAN 30 DEGREES
- IN T AL GM T BE NOT LESS THAN 0.200 m.
- MAXIM M GZ TO BE NOT LESS THAN 0.150 m.

Figure 5.59 The intact static stability criteria.

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MAXIMUM PERMISSIBLE V.C.G. VALUES
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CRITERIA USED IN CALCULATIONS :

1. AREA UP TO 30.0 DEGREES................0.0550 m.rads.
2. AREA UP TO 40.0 DEGREES................0.0900 m.rads.
3. AREA BETWEEN 30.0 AND 40.0 DEGREES......0.0300 m.rads.
4. MAXIMUM GZ TO OCCUR AT.................30.0 degrees
5. MINIMUM GZ AT ABOVE ANGLE............... 0.200 m.
6. MINIMUM GM(FLUID)...................... 0.150 m.
```

DISP tonnes	KG1	KG2	KG3	KG4	KG5	KG6	KG(max)
7000.0	41.195	12.959	18.588	4.188	20.073	6.823	4.188
15000.0	22.334	21.221	19.174	8.875	17.677	7.595	7.595
23000.0	17.087	16.784	15.675	11.875	16.100	8.367	8.367
30000.0	15.067	15.027	15.021	14.313	15.102	9.043	9.043
38000.0	13.665	13.665	14.417	15.578	14.266	9.815	9.815
46000.0	12.893	12.893	13.891	15.250	13.740	10.587	10.587
54000.0	12.606	12.606	13.306	14.313	13.291	11.359	11.359
62000.0	12.555	12.555	12.729	12.063	12.817	12.131	12.063

Figure 5.60 Example of output from the critical KG procedure.

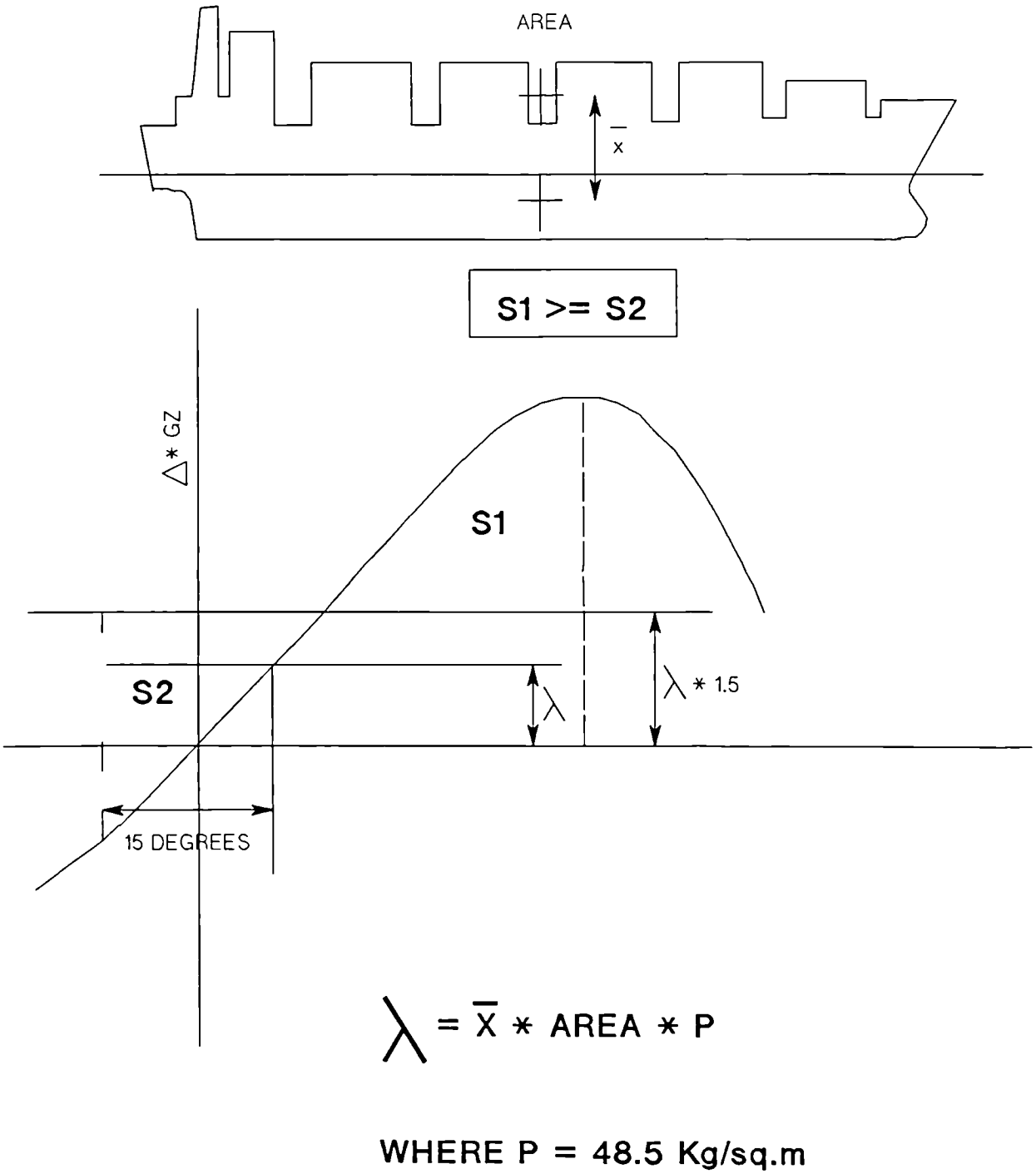


Figure 5.61 The intact dynamic stability criteria.

MAXIMUM ALLOWABLE WIND HEELING MOMENTS

(Tonne.metres)

	VCG(m.A.B.)								
DRAFT(m)	6.000	6.500	7.000	7.500	8.000	8.500	9.000	9.500	10.000
7.000	40868	38075	35312	32353	29440	26624	23656	20905	17893
7.100	41212	38374	35519	32496	29561	26702	23702	20695	17888
7.200	41547	38660	35706	32651	29659	26779	23746	20723	17615
7.300	41862	38950	35893	32792	29778	26854	23802	20742	17610
7.400	42169	39198	36075	32943	29887	26933	23848	20770	17615
7.500	42468	39454	36254	33090	29999	27019	23896	20794	17596
7.600	42737	39680	36435	33223	30101	27081	23947	20581	17584
7.700	43027	39898	36618	33366	30195	27148	23718	20600	17258
7.800	43284	40113	36790	33496	30306	27226	23761	20620	17235
7.900	43541	40324	36963	33633	30401	27283	23814	20641	17217
8.000	43751	40557	37140	33770	30504	27052	23853	20405	17200
8.100	43996	40727	37315	33909	30609	27124	23924	20446	16802
8.200	44206	40907	37500	34063	30711	27200	23986	20474	16780
8.300	44382	41056	37692	34211	30837	27291	23785	20232	16760
8.400	44567	41203	37903	34366	30952	27381	23865	20264	16718
8.500	44719	41321	38009	34524	31081	27494	23943	20319	16694
8.600	44856	41416	38067	34696	31215	27584	24026	20348	16648
8.700	45005	41519	38141	34860	31333	27679	23835	20031	16575
8.800	45120	41603	38182	34898	31453	27780	23924	20053	16497
8.900	45238	41671	38194	34890	31566	27580	23988	20068	16395
9.000	45355	41737	38224	34882	31684	27676	23775	20065	16272
9.100	45429	41767	38240	34874	31776	27764	23832	20034	16136
9.200	45531	41814	38218	34845	31063	27848	23874	20002	15986
9.300	45631	41872	38238	34794	30986	27835	23919	19925	15827
9.400	45649	41879	38204	34729	30931	27246	23332	19857	15529
9.500	45720	41877	38139	34672	30849	27147	23159	19550	15067
9.600	45770	41884	38136	34586	30743	27063	22953	19141	14556
9.700	45802	41858	38051	34485	30653	26935	22725	18694	14524
9.800	45788	41812	37971	34374	30525	26260	22416	18244	14032
9.900	45781	41796	37885	34235	30391	26072	22089	17809	13538
10.000	45763	41747	37800	34119	30240	25911	21742	17309	13322

Figure 5.62 Example of output from the maximum wind-heeling moment procedure.

The second limitation, that imposed by the maximum geometric capacity of the vessel, is related to the number of physical container slots which the vessel possesses. At first sight it could appear that a containership proposal has, theoretically, infinite container stowage space above deck. In fact, the geometric capacity of a vessel will be limited by considerations such as the required line of sight, as shown in Figure 5.63.

2.7.1.3 Economic performance requirements.

The main requirement of any ship design proposal, not just containerships, is that it can be operated with some degree of financial success by the shipowner/operator. It can be appreciated, therefore, that it is not sufficient to simply measure a proposed loading condition against criteria which assess stability and geometric feasibility, but account must also be taken of the profitability, or otherwise, of the proposed condition. In assessing the profitability, or otherwise of a proposed loading arrangement, it is necessary to take into account factors such as fuel price, voyage length, average voyage speed, freight rate, and the level of vessel utilisation, factors which can change on a voyage to voyage basis. In view of the highly variable nature of these factors, it was considered necessary that the loading condition investigation procedures developed for inclusion in the system be able to reflect the effects of changes to the operating parameters defined above.

To allow an assessment of the profitability of proposed conditions to be made, a simplified economic model of containership operation was developed which takes into account the above operating factors. The model basically examines marginal costs and relates these to marginal revenue to arrive at the marginal profit, thus enabling the point at which it becomes non-profitable to add additional containers to the vessel to be determined. In order to simplify the model, it is assumed that the freight rate specified has already been modified to take into account all costs except those associated with the fuel consumption of the vessel. It is appreciated that this assumption is quite significant but it is considered quite reasonable in view of the fact that all that is required is an indication of the profitability of a proposed loading condition. The model is also suited to illustrating the effect of carrying water ballast on the economic performance of the vessel (in terms of the extra income versus the additional fuel costs) and as such is able to demonstrate the flexibility of the design proposal under changing economic conditions.

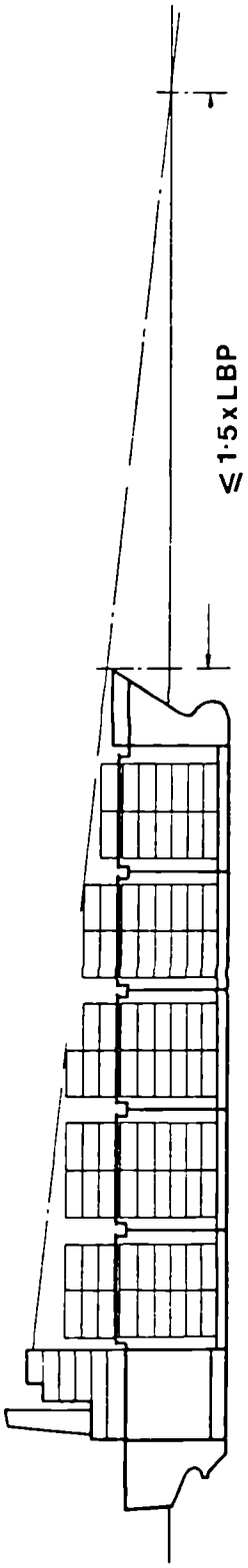


Figure 5.63 Illustration of the line of sight criterion affecting deck-stowage.

The economic model used by the system can be summarised as follows:

$$SD = VL/(VS * 24) \text{ (days)}$$
$$FC = PB * SD * SFOC * 10^{-6} * 24 \text{ (tonnes)}$$
$$C = FC * FP \text{ (\$)}$$
$$P = FR - C \text{ (\$)}$$

where:

SD = Number of days at sea
VL = Voyage length (nautical miles)
VS = Average speed on voyage (knots)
FC = Change in fuel consumption (tonnes)
PB = Change in delivered power due to increased draft (KW)
FOC = Specific fuel oil consumption (g/KWhr)
C = Change in fuel cost ($/container)
P = Change in profitability ($/container)
FR = Net income per container after cargo-handling costs, port charges, capital costs etc., and excluding fuel charges ($)

2.7.2 Methodology of the procedure.

As previously mentioned, the system user is able to define any proposed loading arrangement, be it homogenous or non-homogenous. Using the previously defined container stowage arrangement, the system commences to add containers a tier at a time to the vessel, starting with the hold slots. As each tier is added, an assessment is made of the cargo mass, with the relevant amount being added to the previously determined figure of lightmass and the other deadweight items to give the vessel deadweight. Using this value, the actual vessel draft is determined by interpolation of the previously calculated hydrostatic particulars for the vessel. The maximum permissible vertical centre of gravity of the vessel is also determined at this displacement by interpolation of the previously generated maximum vertical centre of gravity data.

The actual vertical centre of gravity of the vessel is calculated using the previously calculated centroid of the lightmass and that of the other deadweight items, together with the current vertical centroid of the cargo mass. This cargo mass centroid is determined from the detailed knowledge of the location of each container slot on the vessel that the design system has. In the calculation it is assumed that the centroid of

an individual container is located at 45% of the container depth above its base, as this figure is generally considered to be more representative of actual container loadings than simply assuming that the centre of mass location is equal to the geometric centroid position.

Knowing the vessel vertical centre of gravity together with the draft of the vessel, the maximum permissible wind heeling moment is determined by interpolation of previously calculated wind heeling moment data. A routine is used by the system to determine the actual wind heeling moment associated with the current vessel geometry.

Having assembled all of the particulars required to assess the physical feasibility of the condition so far defined, the various associated checks are then carried out. This involves comparing the actual draft of the vessel against the maximum allowable (scantling draft), the actual number of containers loaded against the maximum geometric capacity, the actual vertical centre of gravity against the maximum permissible and the actual wind heeling moment against the maximum permissible.

Provided that none of these checks prove that the condition has failed, the whole process as outlined above is repeated with an additional tier of containers being added. This is repeated until either the maximum draft is reached, the geometric capacity has been achieved, or one of the stability requirements has been violated. If either of the first two limits are reached then no additional containers can be accommodated on the vessel and so the loading process is stopped. However, if one of the stability criteria is violated and there is still sufficient draft and slots available, then there is the option to add water ballast in an attempt to reduce the overall vertical centre of gravity so that more containers can be loaded. It should however be appreciated that the addition of water ballast will not always have a beneficial effect on the vertical centre of gravity of the vessel, as under some circumstances the centroids of the available ballast tanks could be above the current position of the vessel vertical centroid. Filling such tanks would obviously have an adverse effect on the overall centroid of the vessel and should not therefore be carried out. Within the procedure, a check is made on the vertical centroid position of each of the available ballast tanks to determine whether their use would have an overall beneficial effect on the vertical centroid of the vessel. If it is found that some of the tanks available would have a beneficial effect then the one with the lowest vertical centroid will be

filled completely with ballast water and then a check made on whether any more containers can be loaded as a result. This process is repeated until all of the available tanks have been disregarded or filled with ballast, or one of the other limits on loading has been reached. It should also be noted that a check is also made on the trim which would be induced as a result of filling the available tanks, with the selection of the next tank to be filled being based on a combination of longitudinal and vertical position considerations.

In view of the approach outlined above, the need for an accurate definition of ballast tank arrangements and capacities is quite apparent and the author feels that the effort involved in the generation of these tank description is well justified due to the highly flexible nature of the analysis tools which have been developed as a result.

As mentioned previously, the results of any loading operation are presented to the system user in graphical form, thus illustrating the ability of the design proposal to accommodate the proposed condition. Figure 5.64 shows an example of a graphical representation of a defined loading arrangement. As can be seen from the illustration, the curve relating vessel draft to the number of containers carried can be seen to be divided into three distinct regions. The first represents the result of loading the hold slots with containers of the specified mass, with the effect of specifying a tapered loading distribution being quite apparent. The second segment represents the result of adding containers to the deck tiers, with this process being continued until one of the previously mentioned stability requirements is violated. The third part of the line is generated as a result of adding ballast to the double bottom tanks. This part of the curve can be seen to be much steeper than the previous two segments due to the fact that the vessel displacement is being increased more rapidly than before due to water ballast being added to the vessel in addition to the loaded containers. Had all of the slots not been filled, the curve could have become even steeper due to the fact that all of the available double bottom tankage had been used, leaving only the side tanks with their higher vertical centroids. It would therefore have been required to add more ballast to these tanks than was needed in the double bottoms in order to reduce the overall vessel centroid sufficiently to enable additional containers to be loaded. In the given example, the loading process was stopped due to all of the available container slots being filled.

In addition to the graphical representations of the loading condition shown in Figure

5.64, the procedure also produces a tabulated summary of the loading operation showing the vessel particulars at various stages through the loading process. The summary table corresponding to the example condition, shown in Figure 5.64, is given in Figure 5.65. Rather than display the particulars of the vessel at every stage, only the significant stages in the loading process are illustrated. The first one of these is the point where all of the under-deck slots have been filled, with the next one being the point where the vessel has been loaded to its maximum capacity without the addition of any ballast water. After this point a summary of the vessel particulars is given after each ballast tank has been filled, thus illustrating the exact amount of ballast which has to be added in order to accommodate the additional containers.

As can be seen from the example, an indication of the net profit per additional container is given in the final column of the table; this figure being obtained from the operating model described previously. Referring back to the model, it can be seen that the net profit per additional container is dependent upon the increase in fuel consumption caused by the addition of the container mass plus any associated ballast water. In order to determine the increase in fuel consumption it is required to estimate the increase in power needed to maintain the average voyage speed. One possible approach to this problem was to use the previously mentioned Holtrop and Mennen based powering estimation procedure to derive an estimate of the powering requirement at this new vessel displacement. However, this approach does possess one major drawback in that the various coefficients derived by the Holtrop and Mennen analysis were based on data corresponding to the design draft of the vessels involved, and the application of such coefficients to the estimation of powering requirements at partial drafts could prove to be quite inappropriate. In view of this fact it was decided to use the technique developed by Moor and O'Connor [5.33] for the estimation of power requirements at partial drafts. The method involves the use of the previously determined powering data corresponding to the design draft condition with corrections being applied for the partial draft particulars, as indicated below:

$$ {}_{d}\textcircled{C}_{L} = \frac{{}_{d}(ehp)_{L} * 427.1}{{}_{d}\Delta^{2/3}_{L} * V^{3}_{L}} \qquad \text{..... (i)} $$

$$ {}_{d}\textcircled{C}_{400} = (i) + (O_{L} - O_{400})\, {}_{d}\textcircled{S}\, \textcircled{L}^{-0.175} \qquad \text{..... (ii)} $$

$$ {}_{f}\textcircled{C}_{400} = (ii) * (Pe)_R / \Delta^{2/3}_R \qquad \text{..... (iii)} $$

$$ {}_{f}\textcircled{C}_L = (iii) - (O_L - O_{400})\,{}_{f}\textcircled{S}\textcircled{L}^{-0.175} \qquad \text{..... (iv)} $$

where :

$$ {}_{f}\textcircled{S} = {}_{d}\textcircled{S} * \textcircled{S}_R $$

$$ {}_{f}(ehp)_L = \frac{(iv) * {}_{f}\Delta^{2/3}_L * V^3_L}{427.1} $$

where :

$$ {}_{f}\Delta^{2/3}_L = {}_{d}\Delta^{2/3}_L (\Delta^{2/3})_R $$

$$ (Pe)_R = 1 + [(T)_R - 1] * \{(0.789 - 0.270[(T)_R - 1] + 0.529Cb (L/10T)^{0.5}) + (V/\sqrt{L}) * (2.336 + 1.439[(T)_R - 1] - 4.605Cb * (L/10T)^{0.5} + (V/\sqrt{L})^2 * (-2.056 - 1.485\,[(T)_R - 1] + 3.798Cb * (L/10T)^{0.5})\} $$

$(T)_R$ = draft/design load draft

T = design load draft

$\textcircled{S}$ = (wetted surface area) $/\nabla^{2/3}$

$$ \textcircled{S}_R = (T)_R^{-1.0455 - 0.0954Cb(L/10T)1.5 - 0.2008(T)R + 1.2797(T)R} $$

The only disadvantage associated with this technique which could be of some significance to the ship design system, is the fact that the above technique is only applicable to single screw vessels and cannot be used with confidence for the treatment of multi-screw configurations. This is however not considered to be too important as it is envisaged that the vast majority of containership proposals will be of single screw form due to the availability of very high powered slow speed diesel engines and the associated relative simplicity of such installations.

Using the powering data obtained using the above procedure, the operational economics model is used to produce the net profit per container parameter at each of the significant stages described previously. The results from the model indicate to the user the potential profitability of the defined condition and permit him to determine at which point the addition of loaded containers becomes non-profitable. As can be appreciated, any positive value in the net profit column indicates that the carriage of additional containers is worthwhile, whereas a negative value means that the extra

fuel cost incurred as a result of carrying the additional containers outweighs the resulting increase in revenue. The point at which additional containers should not be carried is where the net profit per container is zero. The system permits the user to change the values of the operating parameters and examine the effect on the potential profitability of vessel operations, therefore providing the user with a very powerful aid for the development of containership design proposals.

It was envisaged that the system user would require to investigate a number of possible loading arrangements and compare their potential profitabilities. As a result of this the procedures were developed so as to include the capability of ranking a number of specified conditions according to their potential profitability.

The procedure described above represents the final stage in the development and analysis of a containership design proposal as covered by the system being described here. Presented with the information produced by the loading condition analysis procedure together with the previously generated data concerning the vessel geometry, the system user is in a position to decide whether to further advance the investigation beyond the concept stage or to commence modifications to the existing proposal. If he should decide to carry out modifications to the present design proposal, the system provides him with the required flexibility to investigate the affect on the proposal as a whole, of any of the individual modifications which he desires to make. For example, he may wish to assess the affect of changes in vessel speed on on the overall dimensions of the vessel with or without constraints on some of the associated parameters, or to investigate the affect on dimensions of varying the size of containers carried on the proposal. The implicit structure of the system and the underlying methodology will ensure that such changes are reflected in a consistent and sensible manner.

Whichever option he selects the user can be assured that the proposal produced by the system is based upon the best of current design practice and incorporates many of the features to be found on containerships being built in various shipyards around the world as well as on modern tonnage being presently operated around the world by a number of shipowners.

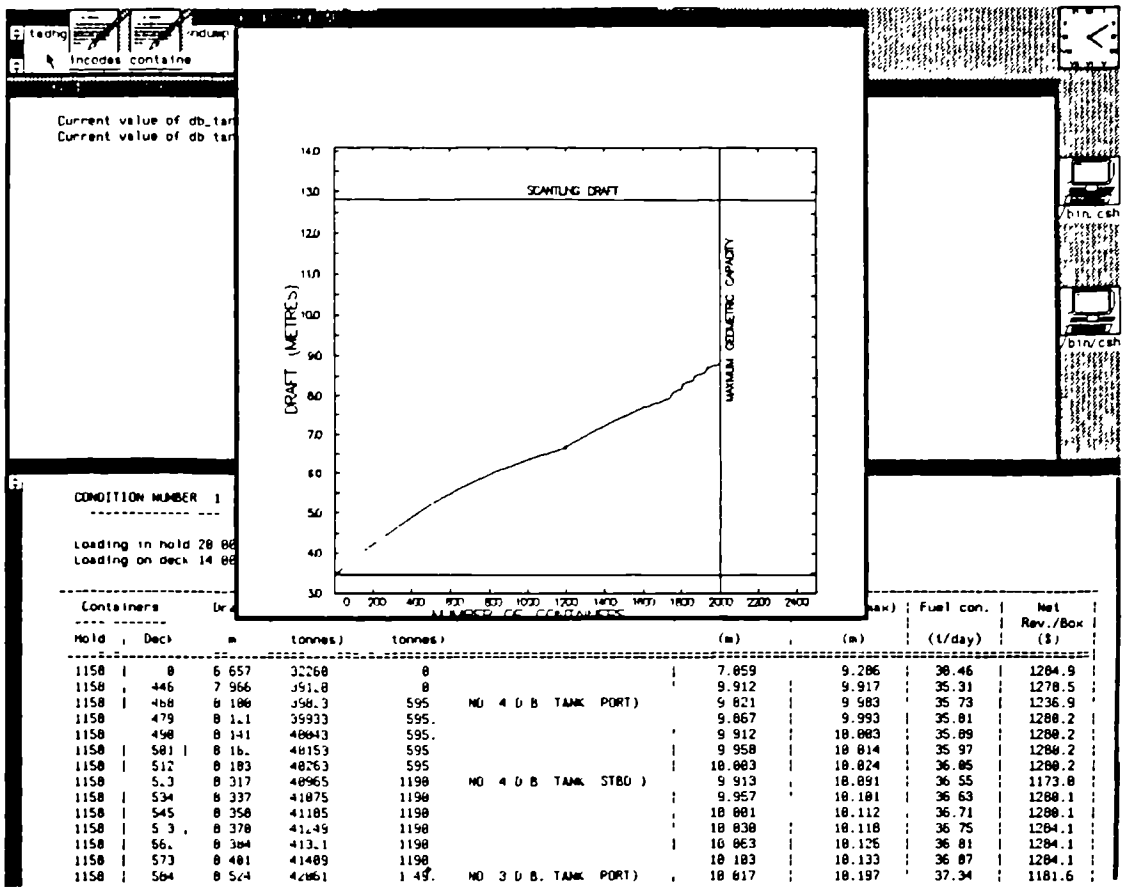
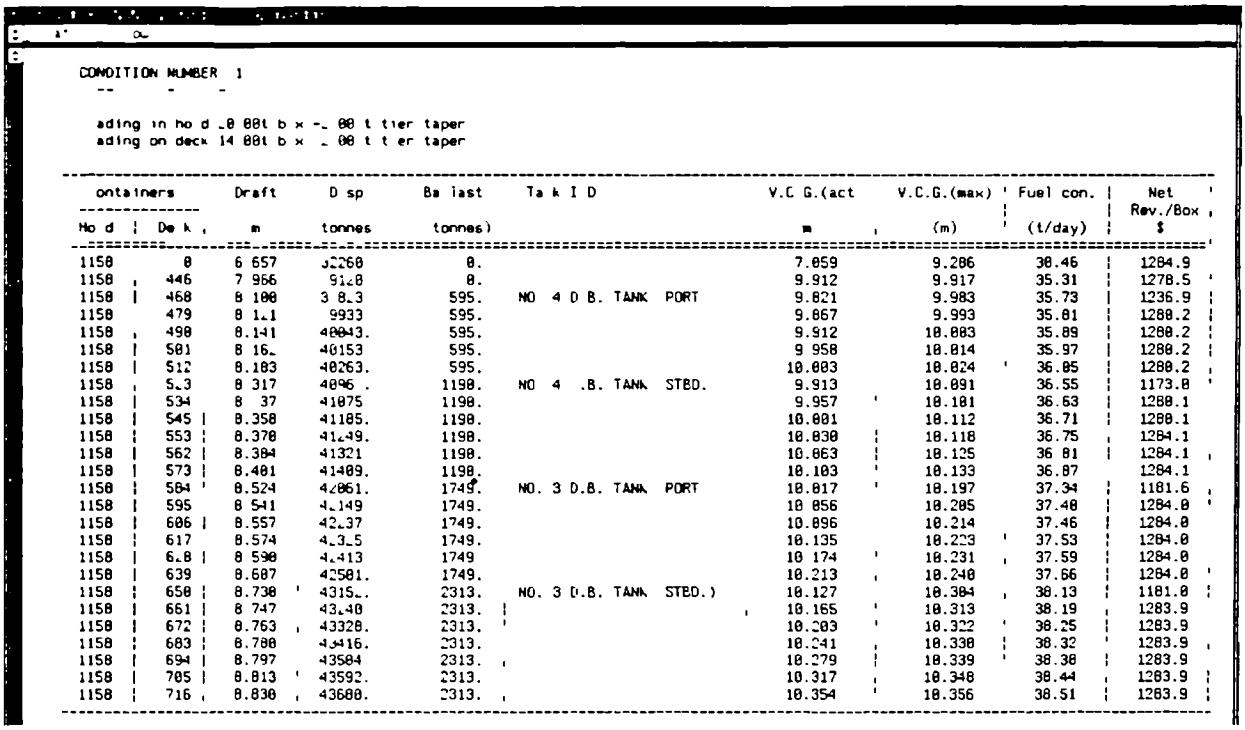


Figure 5.64 Example of a graphical representation of a defined loading condition.



CONDITION NUMBER 1

Hold	Deck	Draft (m)	Displ (tonnes)	Ballast (tonnes)	Tank ID	V.C.G.(act (m)	V.C.G.(max) (m)	Fuel con. (t/day)	Net Rev./Box $
1158	8	6.657	32260	0.		7.059	9.286	38.46	1284.9
1158	446	7.966	9128	0.		9.912	9.917	35.31	1278.5
1158	468	8.100	3 8.3	595.	NO 4 D B. TANK PORT	9.821	9.983	35.73	1236.9
1158	479	8.1.1	9933	595.		9.867	9.993	35.81	1280.2
1158	498	8.141	40043.	595.		9.912	10.083	35.89	1280.2
1158	501	8.16.	40153	595.		9.958	10.014	35.97	1280.2
1158	512	8.183	40263.	595.		10.003	10.024	36.05	1280.2
1158	5.3	8.317	4096.	1190.	NO 4 .B. TANK STBD.	9.913	10.091	36.55	1173.8
1158	534	8 37	41075	1190.		9.957	10.101	36.63	1280.1
1158	545	8.358	41185.	1190.		10.001	10.112	36.71	1280.1
1158	553	8.370	41249.	1190.		10.030	10.118	36.75	1284.1
1158	562	8.384	41321	1190.		10.063	10.125	36 81	1284.1
1158	573	8.401	41409.	1190.		10.103	10.133	36.87	1284.1
1158	584	8.524	42061.	1749.	NO. 3 D.B. TANK PORT	10.017	10.197	37.34	1181.6
1158	595	8 541	4.149	1749.		10 056	10.205	37.40	1284.0
1158	606	8.557	42.37	1749.		10.096	10.214	37.46	1284.0
1158	617	8.574	4.3.5	1749.		10.135	10.223	37.53	1284.0
1158	6.8	8 590	4.413	1749		10 174	10.231	37.59	1284.0
1158	639	8.607	42581.	1749.		10.213	10.240	37.66	1284.0
1158	650	8.730	4315..	2313.	NO. 3 D.B. TANK STBD.)	10.127	10.384	38.13	1181.0
1158	661	8 747	43.40	2313.		10.165	10.313	38.19	1283.9
1158	672	8.763	43328.	2313.		10.203	10.322	38.25	1283.9
1158	683	8.780	43416.	2313.		10.241	10.330	38.32	1283.9
1158	694	8.797	43504	2313.		10.279	10.339	38.38	1283.9
1158	705	8.813	43592.	2313.		10.317	10.348	38.44	1283.9
1158	716	8.830	43680.	2313.		10.354	10.356	38.51	1283.9

Figure 5.65 Tabular representation of defined loading condition.

3. Summary of the containership design knowledge base.

The previous section has described in some detail the considerable scope of the knowledge base which has been developed for the generation of containership design proposals. The knowledge base itself is comprised of statements of heuristic based knowledge together with a vast amount of external analysis procedures. The structure of the knowledge base is such that design proposals can be generated using the heuristic type knowledge and analysed using the external analysis procedures. The INCODES expert system shell, to which the knowledge base is attached, controls the methodology of the design process and decides which information is required from the user at any given time. Being based upon the INCODES expert system shell, the system provides the user with the capability to make any modifications he requires to the emerging proposal, with the result that any of the assumptions made by the system regarding the layout of the vessel, the type of machinery etc., can be overuled and new values supplied. The user is also able to question the reasoning behind the assumptions made and examine the various lines of reaoning which have been followed. Use of the INCODES shell as the basis of the system also means that advice can be incorporated into the knowledge base to provide guidance to the user when required to do so. As can be appreciated from the description of the knowledge base content, the graphics capability of the INCODES shell has been put to good use to enhance both the flexibility and user interface aspects of the design system.

3.1 Knowledge base statistics.

The containership design knowledge base, as described in this Chapter, comprises almost 7,000 lines of INCODES knowledge representation language statements, and references around 80,000 lines of external analysis routines written in FORTRAN 77. The author believes that these figures reflect the highly comprehensive nature of the expert system-based conceptual containership design system which has been developed. It is also considered that this system is perhaps the most comprehensive containership design system presently available in that it examines the containership design problem in much greater depth than any other concept design system, whilst providing the structure required to permit future expansion and enhancement.

A full listing of the containership design knowledge base suitable for attachment to the INCODES expert system shell, together with a listing of the analysis routines source code, can be found in [5.34].

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CHAPTER 6

The Application of the System to the Design of Containerships.

SUMMARY.

This Chapter illustrates how the previously described conceptual ship design system can be applied to the development of containership design proposals. Examples are given which demonstrate the flexibility and scope of the system in its present form as applied to the design of containerships. An indication is given of the quality and extent of the information produced by the various elements of the system, both in terms of the textural and graphical output. The examples given here relate only to those parts of the system which are based upon the INCODES expert system shell, as the capabilities of the other system components which are independent of the expert system (such as the interactive hullform and layout design elements) have already been demonstrated, as illustrated by the papers contained in Appendix I.

1. Introduction.

To demonstrate the capabilities of the present conceptual containership design system based upon the INCODES expert system, examples have been selected which indicate how the system may be used in the development of containership design proposals. These examples illustrate the flexibility of the underlying methodology upon which the design system is based, and provide information about the structure and content of the containership design knowledge base, and the considerable practical design expertise incorporated within it. The examples have been selected so as to provide an indication of the comprehensive nature of the system and the quantity and quality of design data which can be produced.

2. Development of a containership design proposal.

The first example concerns the development of a containership design proposal based upon the following initial design specification:

Maximum capacity:	2000 TEU
Design speed:	20 knots
Cargo handling equipment:	None
Breadth limit:	Panamax 32.2m
Range:	12000 nautical miles
Cargo Mix:	Ability to carry 40ft containers in holds and on deck
Number of deck tiers:	4
Machinery type:	Slow speed diesel.

The above information is used by the design system to arrive at an initial approximation to the number of container bays, rows and tiers needed in order to give the required overall capacity, based upon heuristics contained in the knowledge base. With this starting point, an approximation to the dimensions of the vessel is derived (including allowances in cargo spaces for gaps between containers and generally accepted structural clearances). These approximate dimensions facilitated the generation of appropriate hullform characteristics (e.g. block coefficient and longitudinal centre of buoyancy location). These characteristics are used by the system to assist in the selection of a suitable hullform description from a library of basis vessel forms, as shown in Figure 6.1. With the most suitable hullform having been selected and modified to suit the characteristics of the design proposal (both in terms of dimensions and form characteristics), a check is made on the container capacity of the proposal. In order to do this, an arrangement of holds and hatchways is generated based upon the relevant logic contained in the knowledge base. Procedures are also used to determine the required installed power, and hence the engine to be fitted and size of the engine room to be adopted. To account for the inter-dependencies associated with the parameters involved in the above process, an iterative approach is adopted. In the case of the example being considered here, the above procedure

DESIGN PROPOSAL PARTICULARS

Length between perpendiculars	205.650 m.
Breadth moulded	31.110 m.
Depth moulded to upper deck	18.340 m.
Design draft	12.100 m.
Block coefficient	0.7001
Container capacity @ 20'x 8'x 8'6"	1998
Container capacity @ 40'x 8'x 8'6"	956
Design speed	20.00 knots
Main engine	MAN-B&W 6L90MC
Installed power @ 74 r.p.m.	30240 kW

Table 6.1 Main particulars of the design proposal.

CONTAINER SUMMARY

		TIERS ON DECK			
HOLD No.	UNDER DECK	1	2	3	4
1	46	14	28	42	56
2	234	43	86	129	172
3	252	44	88	132	176
4	252	44	88	132	176
5	126	22	44	66	88
6	126	22	44	66	88
7	118	22	44	66	88
TOTAL	1154	211	422	633	844
	GRAND TOTAL	1365	1576	1787	1998

Table 6.2 Container capacity summary of the proposal.

results in the generation of a proposal with the particulars shown in Table 6.1. A profile of the proposal showing the arrangement of container bays is given in Figure 6.2, together with a section through the midship region of the vessel. The diagram illustrates the vertical and transverse distribution of containers in each of the three hatches to be found in that part of the vessel. Sections through the vessel at the forward and aft ends are shown in Figure 6.3. These illustrations clearly show the results of the steps taken to ensure that shape is taken into account when developing the proposed container arrangement. Figure 6.3 also shows the way in which the arrangement of hatchways is modified to take into account the reduction in deck width towards the ends of the vessel. A complete summary of the full container capacity of the proposal is produced, as shown in Table 6.2. The table illustrates that a tolerance is necessary on the specified capacity because of the non-linear relationship between containership capacity and vessel size which will usually prevent an exact capacity from being achieved.

At this stage in the proceedings, an assessement of the tank capacity of the vessel is made, with respect to both double bottom and side tanks. The results of this assessment are shown in Table 6.3 which also serves to illustrate the comprehensive nature of the particulars generated for each of the tanks which can be accommodated in the vessel arrangement. In addition to providing a comprehensive means of checking the available tankage in the vessel, these particulars are used to investigate the flexibility of the proposal in terms of its ability to accommodate various loading arrangements and distributions of container mass. Loading conditions can be displayed graphically showing the relationship between vessel draft, stability characteristics, displacement, vessel marginal profitability and the number of containers carried. This form of presentation allows the condition to be examined as the vessel is gradually loaded with containers of a specified mass. The vertical distribution of the containers can be varied to give a tapering effect, with the hold and deck-stowed containers being treated separately. Figure 6.4 shows a typical example of the graphical output for part of a specified uniform loading arrangement. This diagram clearly shows the effect of successively adding containers in the holds of the vessel, with a mass of 14.0 tonnes each, and then onto the hatch covers with a mass of 10.0 tonnes. This example also illustrates the way in which ballast water can be added to the previously defined tanks to increase the number of containers which can be accommodated whilst satisfying the IMO stability criteria. Figure 6.5 shows a graphical summary of three

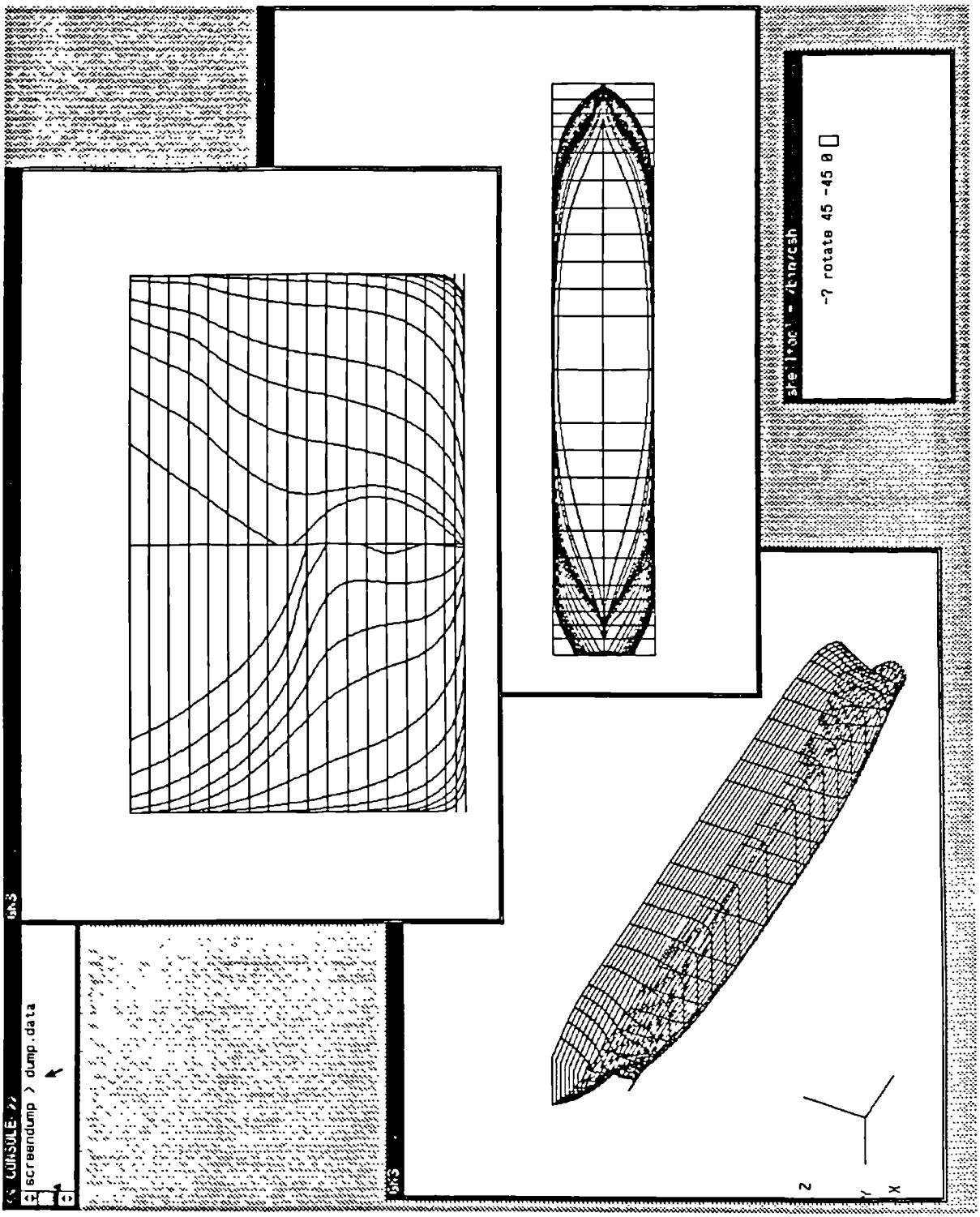


Figure 6.1 Graphical representation of the hullform of the design proposal.

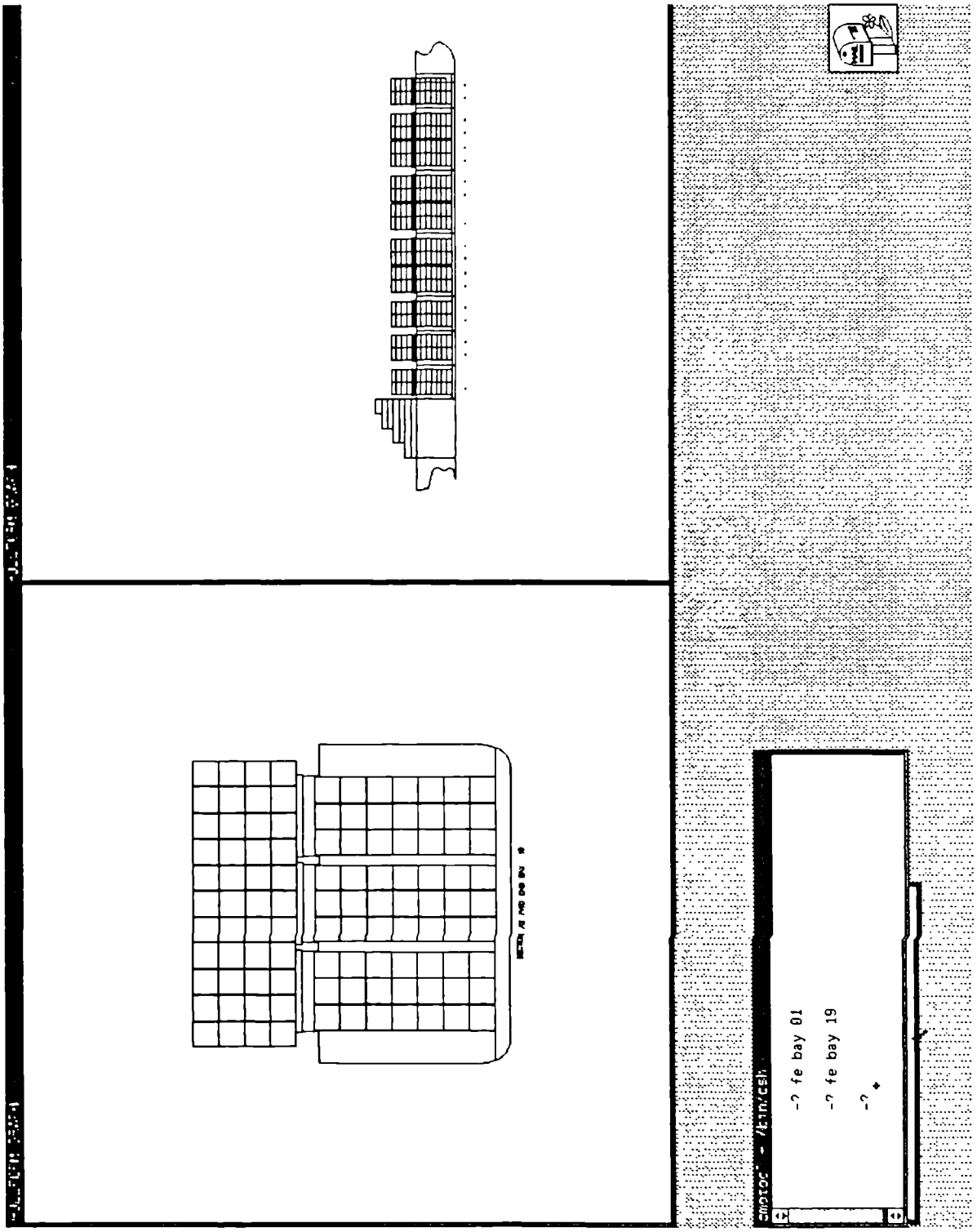


Figure 6.2 Profile and midship section of the design proposal.

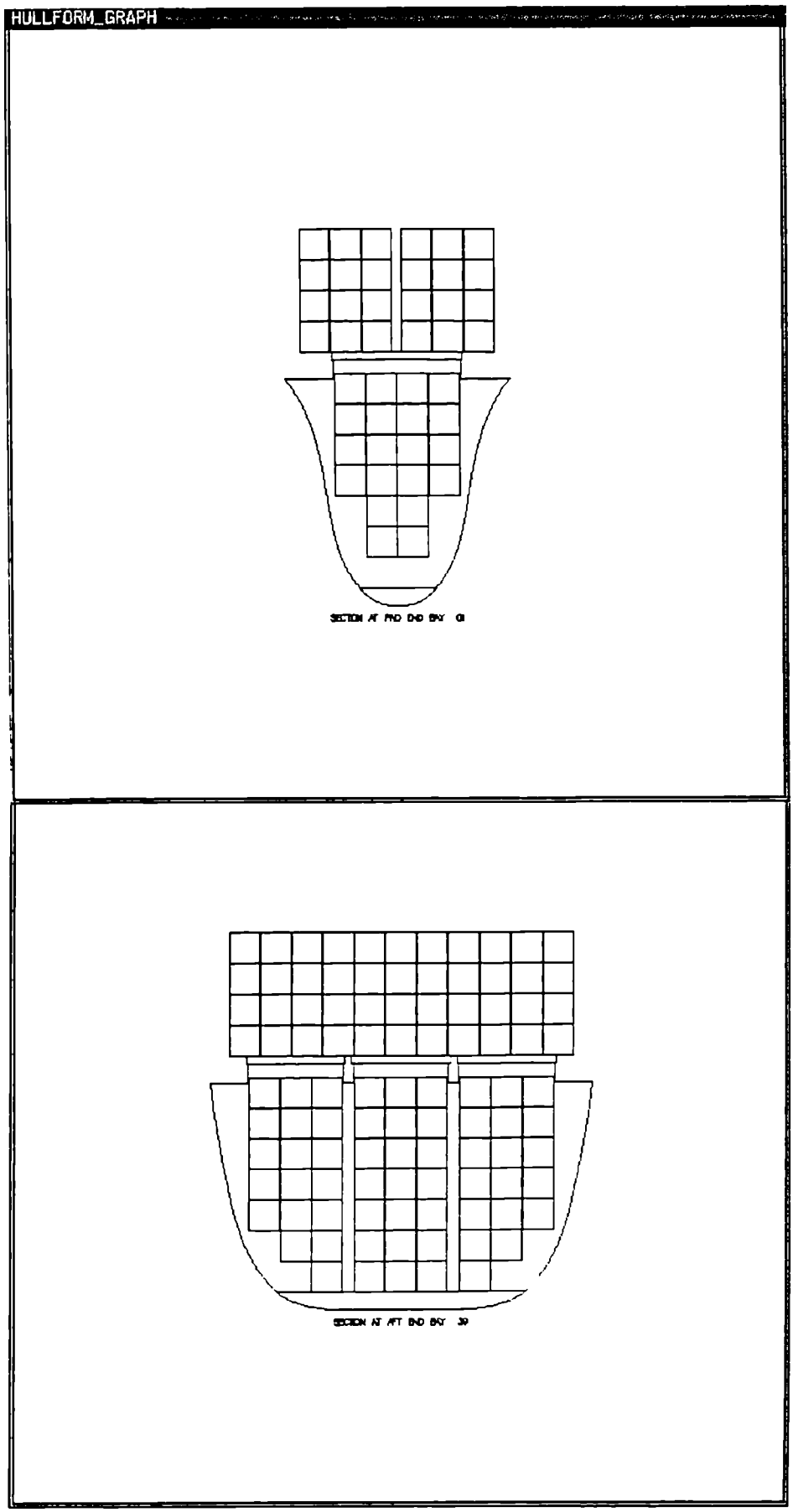
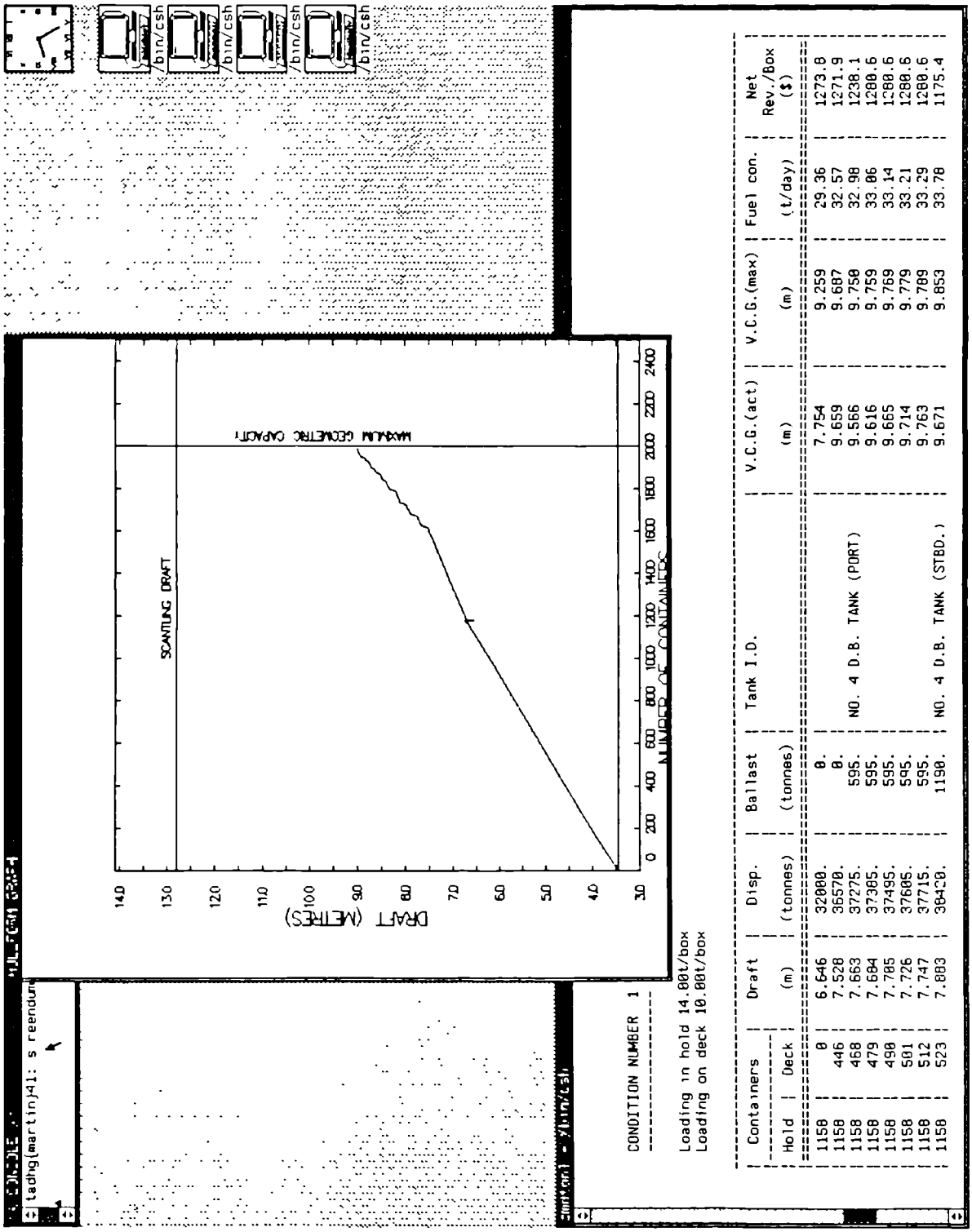


Figure 6.3 Sections through the proposal at the forward and aft ends.

	TANK	CAPACITY (m3)
1	NO. 1 D.B. TANK (PORT)	120.5
2	NO. 1 D.B. TANK (STBD)	120.5
3	NO. 2 D.B. TANK (PORT)	456.6
4	NO. 2 D.B. TANK (STBD.)	456.6
5	NO. 3 D.B. TANK (PORT)	563.6
6	NO. 3 D.B. TANK (STBD.)	563.6
7	NO. 4 D.B. TANK (PORT)	592.7
8	NO. 4 D.B. TANK (STBD.)	592.7
9	NO. 5 D.B. TANK (PORT)	307.0
10	NO. 5 D.B. TANK (STBD.)	307.0
11	NO. 6 D.B. TANK (PORT)	270.0
12	NO. 6 D.B. TANK (STBD.)	270.0
13	NO. 7 D.B. TANK (PORT)	202.0
14	NO. 7 D.B. TANK (STBD.)	202.0
15	NO. 1 HOLD SIDE TANK (P)	2388.9
16	NO. 1 HOLD SIDE TANK (S)	2388.9
17	NO. 2 HOLD SIDE TANK (P)	5979.0
18	NO. 2 HOLD SIDE TANK (S)	5979.0
19	NO. 3 HOLD SIDE TANK (P)	6621.9
20	NO. 3 HOLD SIDE TANK (S)	6621.9
21	NO. 4 HOLD SIDE TANK (P)	6637.2
22	NO. 4 HOLD SIDE TANK (S)	6637.2
23	NO. 5 HOLD SIDE TANK (P)	3563.1
24	NO. 5 HOLD SIDE TANK (S)	3563.1
25	NO. 6 HOLD SIDE TANK (P)	3497.9
26	NO. 6 HOLD SIDE TANK (S)	3497.9
27	NO. 7 HOLD SIDE TANK (P)	3287.1
28	NO. 7 HOLD SIDE TANK (S)	3287.1

Table 6.3 Tank capacity summary for the design proposal.



Containers Hold	Containers Deck	Draft (m)	Disp. (tonnes)	Ballast (tonnes)	Tank I.D.	V.C.G.(act) (m)	V.C.G.(max) (m)	Fuel con. (t/day)	Net Rev./Box ($)
1158	0	6.646	32000.	0.		7.754	9.259	29.36	1273.8
1158	446	7.528	36570.	0.		9.659	9.687	32.57	1271.9
1158	468	7.663	37275.	595.	NO. 4 D.B. TANK (PORT)	9.566	9.750	32.98	1238.1
1158	479	7.684	37385.	595.		9.616	9.759	33.06	1280.6
1158	490	7.705	37495.	595.		9.665	9.769	33.14	1280.6
1158	501	7.726	37605.	595.		9.714	9.779	33.21	1280.6
1158	512	7.747	37715.	595.		9.763	9.789	33.29	1280.6
1158	523	7.883	38420.	1190.	NO. 4 D.B. TANK (STBD.)	9.671	9.853	33.78	1175.4

Figure 6.4 Graphical representation of a uniform loading arrangement.

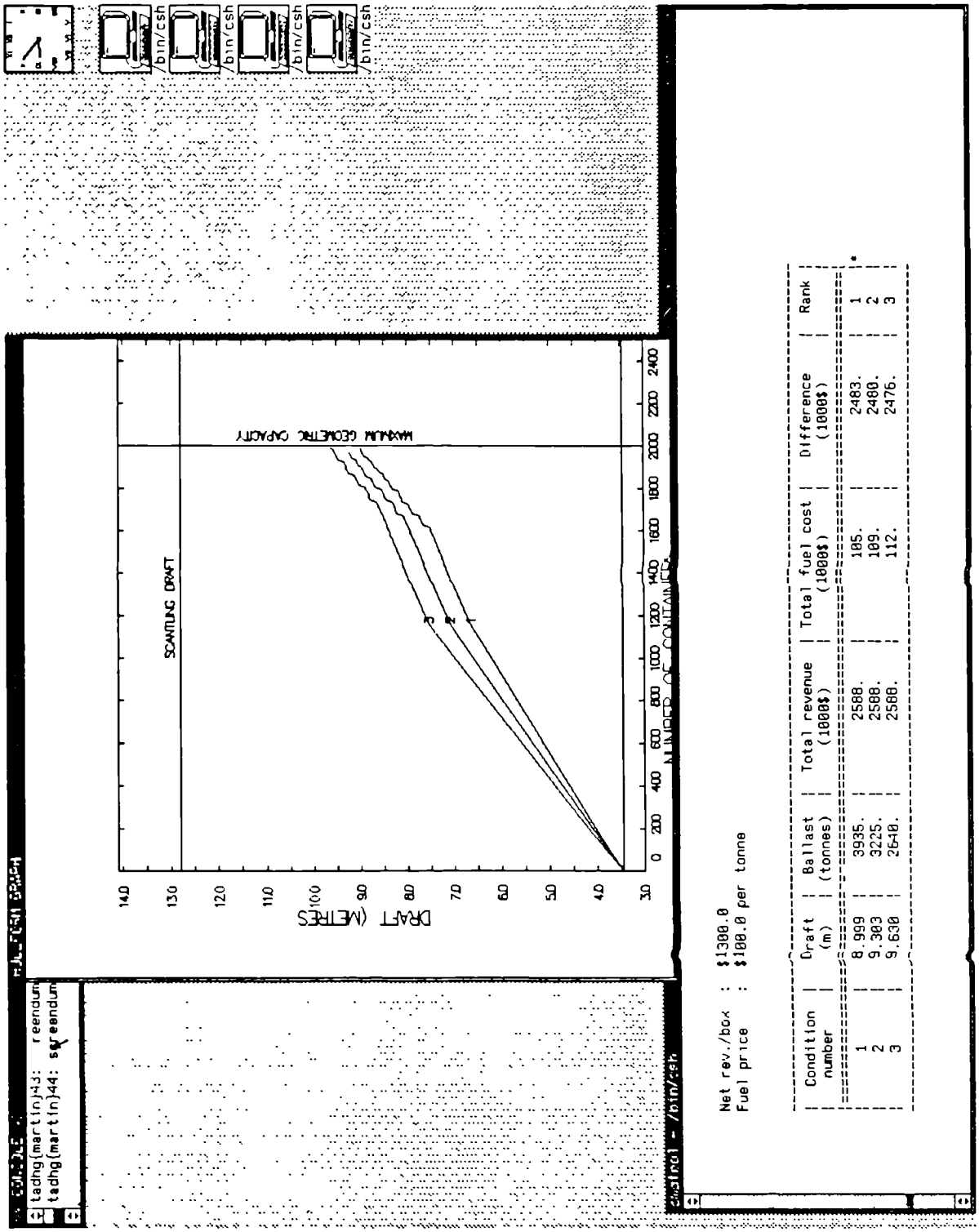
uniform loading conditions with the table indicating their rank when assessed in terms of the net difference between total revenue and total cost.

An example of a non-uniform loading condition is given in Figure 6.6, which shows the way in which more realistic representations of actual vessel loading arrangements can be obtained. This particular condition indicates a tapered mass distribution in both the holds of the vessel and on the deck, which is more representative of the loading arrangements to be found in reality. The example clearly shows the benefits to be gained from using such distributions in terms of required ballast and hence the effect on vessel profitability.

3. The effect of changes in ship speed on the main ship characteristics.

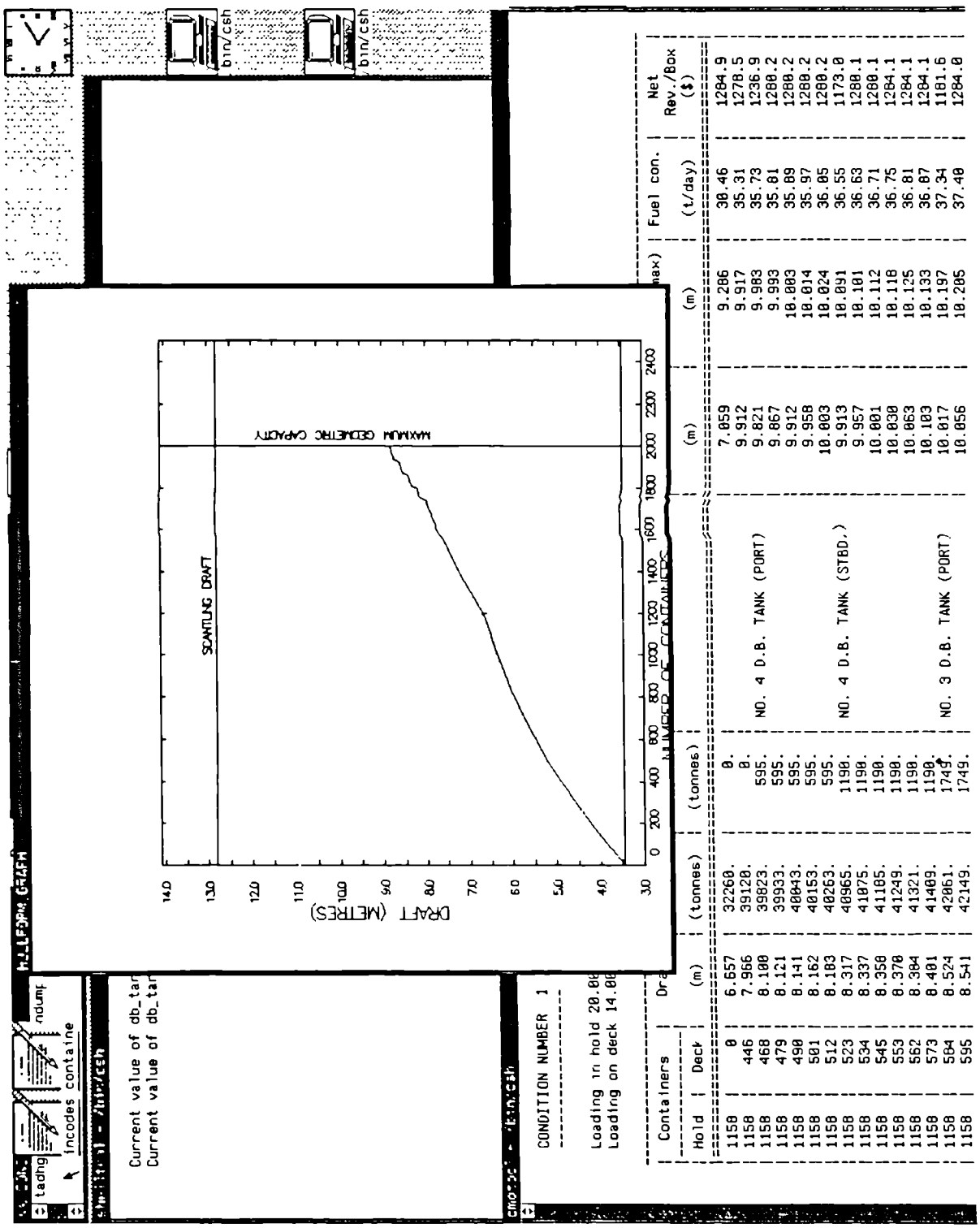
This second example demonstrates the use of the system in a sensitivity study in which it is essential that the design methodology incorporated in the knowledge base functions consistently. In this study three designs are generated having the same specified container capacity but significantly different design speeds. The basic specification for the design proposals is assumed to be the same as in the previous example.

The system is used to generate design proposals for three vessels having speeds of 19, 21 and 23 knots respectively. The outline design particulars produced by the system are shown in Figure 6.7. A profile of each of the design proposals is given in Figure 6.8 together with a section through the forward cargo region of each one. As can be seen from the particulars, the most obvious effect of changing design speed is the resulting modification to the length of the vessels. The primary cause of this change in the 21 and 23 knot variants is the increase in engine room length caused by the need to install a more powerful and hence larger engine. The installation of this larger engine not only directly increases the length of the engine room, but also causes the engine room to be positioned further forward in the vessel in order that the greater width of engine can be accommodated on the tank top. A further cause of the increase in length is the change in the block coefficient and the need to achieve a certain displaced volume. Restrictions placed on the breadth of the vessels prevents this parameter from being changed, and while there is some change in the drafts of the vessels the main changes are made to the lengths. As can be seen from the particulars of the design proposals, the change in the associated block coefficients has an affect on the number of containers which can be accommodated in each of the



Condition number	Draft (m)	Ballast (tonnes)	Total revenue (1000$)	Total fuel cost (1000$)	Difference (1000$)	Rank
1	8.999	3935.	2588.	105.	2483.	1
2	9.303	3225.	2588.	109.	2480.	2
3	9.630	2640.	2588.	112.	2476.	3

Figure 6.5 Summary of three uniform loading arrangements.



Hold	Deck	(m)	(tonnes)	(tonnes)		(m)	(m)	Fuel con. (t/day)	Net Rev./Box ($)
1158	0	6.657	32260.	0.		7.059	9.286	30.46	1284.9
1158	446	7.966	39120.	0.		9.912	9.917	35.31	1278.5
1158	468	8.100	39823.	595.	NO. 4 D.B. TANK (PORT)	9.821	9.983	35.73	1236.9
1158	479	8.121	39933.	595.		9.867	9.993	35.81	1280.2
1158	490	8.141	40043.	595.		9.912	10.003	35.89	1280.2
1158	501	8.162	40153.	595.		9.958	10.014	35.97	1280.2
1158	512	8.183	40263.	595.		10.003	10.024	36.05	1280.2
1158	523	8.317	40965.	1190.	NO. 4 D.B. TANK (STBD.)	9.913	10.091	36.55	1173.0
1158	534	8.337	41075.	1190.		9.957	10.101	36.63	1280.1
1158	545	8.358	41185.	1190.		10.001	10.112	36.71	1280.1
1158	553	8.370	41249.	1190.		10.030	10.118	36.75	1284.1
1158	562	8.384	41321.	1190.		10.063	10.125	36.81	1284.1
1158	573	8.401	41409.	1190.		10.103	10.133	36.87	1284.1
1158	584	8.524	42061.	1749.	NO. 3 D.B. TANK (PORT)	10.017	10.197	37.34	1181.6
1158	595	8.541	42149.	1749.		10.056	10.205	37.40	1284.0

Figure 6.6 Graphical representation of a non-uniform (tapered) loading arrangement.

DESIGN PROPOSAL PARTICULARS

Length between perpendiculars	202.034 m.
Breadth moulded	31.110 m.
Depth moulded to upper deck	18.340 m.
Design draft	12.400 m.
Block coefficient	0.7872
Container capacity @ 20'x 8'x 8'6"	2022
Container capacity @ 40'x 8'x 8'6"	990
Design speed	19.00 knots
Main engine	MAN-B&W 5L90MC
Installed power @ 74 r.p.m.	25200 kW

DESIGN PROPOSAL PARTICULARS

Length between perpendiculars	212.880 m.
Breadth moulded	31.110 m.
Depth moulded to upper deck	18.340 m.
Design draft	12.660 m.
Block coefficient	0.6802
Container capacity @ 20'x 8'x 8'6"	1996
Container capacity @ 40'x 8'x 8'6"	952
Design speed	21.00 knots
Main engine	MAN-B&W 7L90MC
Installed power @ 74 r.p.m.	35280 kW

DESIGN PROPOSAL PARTICULARS

Length between perpendiculars	218.650 m.
Breadth moulded	31.110 m.
Depth moulded to upper deck	18.340 m.
Design draft	12.680 m.
Block coefficient	0.6291
Container capacity @ 20'x 8'x 8'6"	1978
Container capacity @ 40'x 8'x 8'6"	935
Design speed	23.00 knots
Main engine	MAN-B&W 7L90MC
Installed power @ 74 r.p.m.	35280 kW

Figure 6.7 General particulars of three design proposals.

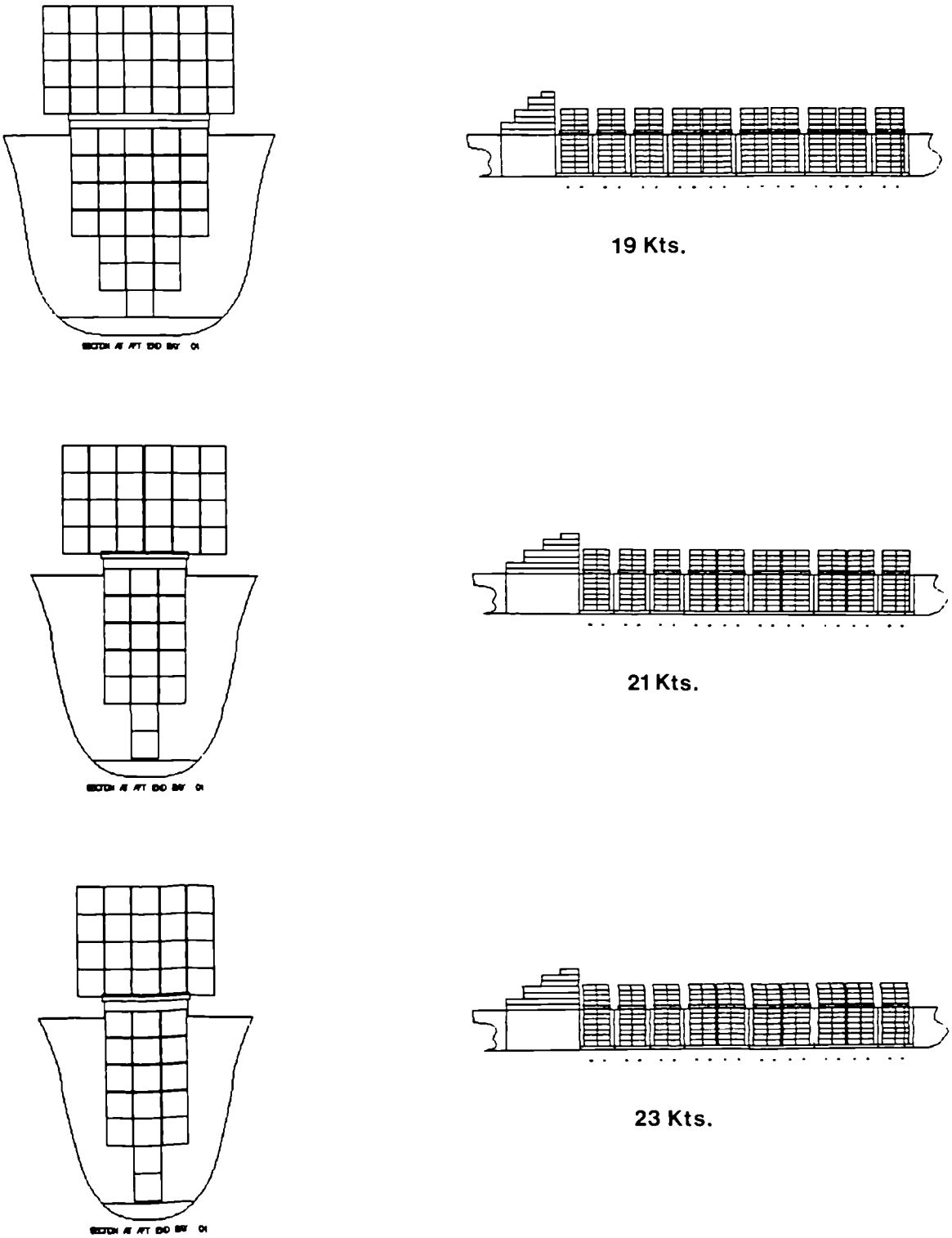


Figure 6.8 Profile and forward section of each design proposal.

arrangements. These changes do not, however, cause an increase in the numbers of bays, rows or tiers of containers, as each of the final capacities is still within the tolerance accepted by the system.

Although the above is a relatively simple example, it does illustrate the ease with which design investigations can be carried out and the manner in which constraints can be applied and design parameters varied. This example, together with the previous one, demonstrates the considerable capabilities of the system and illustrates the consistent and thorough manner in which design investigations can be undertaken.

As an indication of the type of dialogue which takes place between the user and the design system during a typical run, graphical displays of the workstation monitor at various stages during a run are given in Appendix II. These graphics illustrate the way in which the user is kept informed as to the progress being made in terms of the design variables which have been determined, and also the way in which the user can interrogate the system to determine where particular parameters are assigned and to examine the logic being used.

CHAPTER 7

Conclusions and Further Work.

SUMMARY.

This Chapter summarises the results of the research project carried out and indicates where, in some cases, a different approach could have had a beneficial affect on the outcome of the project. The areas where further effort is seen to be required to improve the present system are outlined, as are those areas considered suitable for possible future extension.

1. Introduction.

The previous chapters of this thesis have described in some detail the computer based system which has been developed for the conceptual design of ships, with particular emphasis being on the design of containerships. The reasons behind the adoption of an expert system approach to the development of the design system have been explained, as have the reasons for developing a unique expert system shell to form the basis of the system. The various aspects of the design of containerships have been discussed, especially those which combine to make the containership such a unique and interesting design problem. The expert system knowledge base, which was developed to assist in the development of containership design proposals, has been described in some detail with the reasoning behind the in-built design logic being made apparent.

The decision to select the containership as the vessel type to be given prime consideration in the development of the concept design system has been proven to be worthwhile, especially as this particular vessel type provided a considerable challenge at every stage in the development of the system methodology. The containership concept also proved to be an excellent test for the capabilities of the INCODES

expert system shell which was developed specifically to form part of a general concept design system. The attempts to make some parts of the system ship-type independent also proved to be quite successful, with many of the external analysis procedures being capable of dealing with vessels of any type. This is also true for the hullform development procedures which have been structured in such a way so as to make them applicable to the development of virtually any type of vessel hullform, regardless of the type of features incorporated into the form. To some extent the interactive layout and compartmentation routines can also be said to be non ship-type specific, although they would require some enhancement in certain areas in order to provide them with the capability of modelling particular vessel types such as bulk carriers. Such enhancements will be discussed later.

Although primarily intended to function as a complete sub-system of the complete British Shipbuilders/University of Newcastle conceptual ship design system described in Chapter 1 of this thesis, the various components of the sub-system described here were developed on a stand-alone basis so that they could be used equally effectively as separate routines. In this respect all the analysis routines can be used as individual programs as can the hullform definition and interactive layout/compartmentation procedures, as illustrated by the references previously mentioned and contained in Appendix I. The stand-alone capability of the various sub-system components is also evident from the format of the user documentation for the system as contained in [7.1], [7.2] and [7.3]. This modularity has enabled rapid testing and verification of the components to be carried out and has also permitted them to be released to industry as and when they became available. In fact, stand-alone versions of the hullform definition procedure and the interactive layout/ compartmentation routines were handed over to the research sponsors some considerable time before the completion of the remaining components.

With reference to the complete conceptual ship design system described in Chapter 1, of which this work is part, the interfaces required to enable the transfer of information to the other sub-systems such as the structural definition and steelmass estimation, and the work content and cost estimation sub-systems, have been developed and implemented and shown to be functioning correctly. Thus the data concerning the definition of the basic characteristics of a design proposal, such as the main dimensions, hullform description, layout particulars and loading arrangements, can be passed to the other elements of the complete system and used as the basis for their analysis.

This has resulted in the initial concept, developed over four years ago, of a fully integrated conceptual ship design system based upon a desktop computer, becoming a reality [7.4]. Thus providing the designer with an integrated design tool capable of developing and analysing design proposals at a level of detail, and in a time-scale, which was previously totally impossible.

As with any project of this nature, a number of assumptions and decisions were made during the development of the sub-system described here, which were as a result of constraints imposed by time limitation and the need to simplify the problem in some areas. With the benefits of hindsight it can also be said that some aspects of the system could have been improved had a slightly different approach been adopted in these areas. It must be said, however, that the shortcomings of the system are vastly outweighed by the outstanding features that it possesses.

2. The INCODES expert system shell.

The many valid reasons for using expert system based applications in engineering design have already been discussed in previous Chapters of this thesis and will not be repeated here. It is, however, necessary to emphasise the fact that expert systems are considered to possess enormous potential as intelligent aids in the area of engineering design. It should be noted however, that the development and implementation of expert systems (a very long and involved task in itself) is not a guarantee of improvements in design productivity, quality or innovation, but can, if viewed realistically, be seen as a means of complementing and enhancing existing design activities. The author considers that many current and future examples of expert system applications will result from attempts by the participating organisations to rectify problems or shortcomings which are of a much more fundamental nature than would appear at first sight. In such cases the implementation of expert system applications could have a highly detrimental effect on the situation with the result that the expert system concept is unfairly discredited to some degree. In fact, it is widely accepted that expert system applications should only be introduced into a commercially stable environment in order that the application has the chance to become established and prove its worth within the existing operation, otherwise it is doomed to failure from the start.

2.1 Advantages of the INCODES shell.

The decision to develop a unique expert system shell specifically to form the basis of the concept design system was mainly taken as a result of the disadvantages associated with the commercially available shells. This decision, together with the one taken to write the shell in FORTRAN 77, were considered at the time to be quite radical. The success of the project has vindicated these decisions, and in fact it is considered that the outcome might not have been so successful had a different approach to the problem been adopted and a commercially available shell used.

The shell itself fulfills all of the basic requirements specified for it as described in Chapter 3. In addition to providing the controlling mechanism for the concept ship design system described here, it also offers considerable potential for the development of other expert system applications. In fact, there has already been some interest shown in the INCODES expert system shell as a possible base for the development of other engineering related applications, by a prominent marine consultancy, in the area of the selection of fire-fighting equipment.

One of the main features of the INCODES shell which has contributed significantly to its success is the knowledge representation language (KRL) developed by the author to form part of the shell. This unique language provides a very user-friendly means of representing various types of knowledge. The structure and syntax of the INCODES KRL are such that they provide a high degree of flexibility in the creation of application knowledge bases. The feature of the system which permits the user to customise the syntax of the knowledge representation language is seen as a means of improving the user-friendliness of the shell, and is considered by the author to be a feature unique to the INCODES system.

The considerable capabilities of the INCODES shell in terms of mathematical and scientific funtionality, makes it ideally suited to engineering applications development and is a feature which makes INCODES vastly superior to most of the presently available commercial shells in this application area. The ability of INCODES to interface easily with graphical procedures greatly increases the effectiveness of any application. In addition, the feature of the shell which permits access to external routines written in high level languages considerably increases the analysis capabilities of any application, which again makes the system ideally suited to the solution of

engineering problems.

2.2 Shortcomings of the INCODES expert system shell .

Although the development of the INCODES shell is considered to have been largely successful, there are a number of points concerning the shell which could have been improved upon.

The main area of concern in the INCODES shell is associated with the knowledge representation compiler developed to translate the knowledge representation language statements contained in a particular knowledge base into valid FORTRAN 77 statements suitable for compilation by the ANSI standard FORTRAN 77 compiler. Although the KRL compiler carries out this process both efficiently and accurately, where it is vulnerable is in its error trapping capability. Provided that all of the statements in a particular knowledge base are correct, then the equivalent FORTRAN 77 statements created will also be structurally and syntactically correct. The inability of the KRL compiler to recognise some types of error within a knowledge base can lead to the generation of invalid FORTRAN in some cases. It is therefore necessary at present for the knowledge base author to ensure that all of the knowledge base statements are correct otherwise some of the errors could propogate through to the FORTRAN 77 code which would then cause problems for the FORTRAN 77 compiler. It is therefore considered necessary to improve the error trapping capabilities of the INCODES KRL compiler in order to remove the responsibility from the knowledge base author to ensure that the knowledge base is structurally and syntatically perfect before compilation is attempted.

2.3 Possible future enhancements to the INCODES shell.

Apart from the existing shortcomings of the INCODES shell described above, there are a number of enhancements which could be made to the shell and which were outside the scope of the present project.

The first of these enhancements concerns the capability of the shell to reason with uncertain knowledge. At present, the knowledge representation language and the inference engine of the INCODES shell are only capable of reasoning with concepts expressed in terms of classical boolean logic that is the system can only represent two states, true and false. As discussed in Chapter 2 of this thesis, many real-life situ-

ations involve other levels of certainty such as absolutely true, possibly true, unknown, possibly false and absolutely false. In addition to this multi-valued boolean logic, the existance of fuzzy logic was also discussed earlier in this thesis. The ability of fuzzy logic to represent a theoretically infinite number of levels of certainty makes it a very powerful means of reasoning with uncertain knowledge. It is therefore proposed that the INCODES shell would benefit considerably from the inclusion of fuzzy logic theory as an aid to the decision making process. Such a feature would permit the system user to assign levels of certainty to his responses to system questions, ranging from 1, which indicates absolute certainty to 0 which indicates complete uncertainty. The lack of such a facility within INCODES did not effect the development or use of the application described here, but could be a consideration in the specification and development of future INCODES applications.

Another enhancement to the shell could be the inclusion of a rule induction facility for the automatic generation of knowledge base rules. A number of existing shells do claim to provide a learning capability, but in many cases this simply involves a run-time knowledge base editing feature which permits the user to modify the contents of the knowledge base during a consultation session. Although this could possibly be argued to be a form of learning, it still relies upon the user to define the various rules and relationships relevant to the problem domain. A true learning capability involves the expert system actually deriving new rules and relationships by examination of data obtained from some data collection facility. In its most basic form, this rule induction process could involve the expert system simply carrying out some form of regression analysis on data to determine the possible existance of relationships between the relevant parameters. The second technique used for the automatic development of rules is that which derives rules from examples provided by the user. This is really an automated form of knowledge elicitation based upon a type of protocol analysis as described in Chapter 5 of this thesis.

It is considered that the incorporation of some form of machine learning facility into the INCODES shell would be of considerable benefit to any proposed application. The basic rule induction process, the data analysis (regression analysis) aspect, could prove very useful in the derivation of empirical relationships between the various parameters in any engineering design applications. The inclusion of an induction facility based upon learning by example could also bring a number of advantages in that it could be used for the derivation of causal relationships (deep relationships)

between the various parameters in the problem domain.

One final enhancement to the shell which would improve its appeal to potential users would be its transfer to other computer systems, a move which would considerably increase its potential user base. Transfer of the shell to other UNIX based machines would not present any problems and would only require a simple re-compilation to create the relevant run-time image of the shell. In machines which utilise operating systems other than UNIX, such as DOS based 80286 and 80386 systems, the transfer process could present minor problems, although it is envisaged that none of these would be insurmountable. It should, however, be noted that the overall complexity of the knowledge bases which could be attached to INCODES on these PC type systems, would be limited by the total usable memory available on such machines. For example, the containership design application described here, would not run on the majority of these smaller machines due to its requirement for at least 8 megabytes of addressable memory. This extraordinary memory requirement is due almost completely to the size and complexity of the external analysis routines used by the knowledge base for the verification of design proposals.

3. The containership design knowledge base.

As previously mentioned, the containership design knowledge base developed by the author for attachment to the INCODES expert system shell comprises approximately 7,000 lines of INCODES knowledge representation language statements, supported by around 80,000 lines of FORTRAN 77 analysis routines.

3.1 Main features of the knowledge base.

The approach adopted for the development of the containership design system has resulted in what the author considers as perhaps the most comprehensive design system for container carrying vessels currently available. It provides a unique combination of synthesis and analysis procedures which enable design proposals to be developed at a level of detail which has not been possible before now. This depth of investigation arises from the fundamental nature of the techniques used in the synthesis and analysis of the design proposals. The system is considered to be unique in its use of complex modelling techniques, such as surface representations, in a system which is intended to be used primarily as an aid in concept design studies. This has

been achieved by structuring the various procedures in such a way that the underlying theory is transparent to the user and he is unaware of the complexities of the techniques being used. The provision of a highly user-friendly interface to these procedures (involving interactive graphics in many cases) can only encourage design activity and innovation as a result of increased user confidence in the system. Even when used as a stand-alone units, the author believes that the components of the system developed as part of this project provide the user with a very powerful and comprehensive suite of design and analysis procedures. The hullform design and interactive layout/compartmentation in particular, provide an extremely versatile design and analysis capability when used in the stand-alone mode.

In fact, these two components of the system have been adopted by Marine Design Consultants Limited to form their CHAS (Computerised Hullform and Compartmentation Sketchpad) system ([7.5], [7.6]).

Throughout the development of the system the use of approximate calculation procedures in areas such as stability, hydrostatics and capacities has been judiciously avoided, with the emphasis being on the utilisation of full calculations which conform to accepted procedures. Such a policy not only encourages confidence in the results produced by the system at the concept stage, but also allows the procedures to be used in detail design investigations.

As a result of developing the procedures with the aim of using them at later stages of the design process, many of the procedures incorporate features which are not utilised at the concept stage, but are thought by the author to enhance considerably the system as a whole. These features include the ability to model appendages, thruster openings etc, in the hydrostatics and stability calculations, a level of detail which may be considered unnecessary even within the concept design system described here, but which would be of some significance at the detailed design stages.

The containership design system as a whole provides a means of investigating many aspects of containership design at a level which was previously not possible. In particular the ability provided by the system to model containership operations on a realistic basis will be, it is considered, invaluable to both the containership designer and the containership operator. In addition to allowing the flexibility of proposed designs to be demonstrated to prospective owners, the techniques used in the system

would permit the operators of existing vessels to examine the effect of changing operating parameters or changes in container weights on the operational charcteristics of the vessels. The ability provided by this system to examine the effect of variations in loading arrangements in such detail is considered to be quite unique with such a feature being beyond the scope of any of the concept ship design systems known to the author.

3.2 Shortcomings of the containership design knowledge base.

Despite the obviously highly comprehensive nature of the knowledge base developed for the conceptual design of containerships, there are a number of specific areas which would benefit from receiving further consideration.

One particular area which could be improved upon is that concerned with the estimation of the lightmass particulars of the vessel. At the present time the knowledge base utilises the empirical relationships developed by Bentley for the estimation of steelmass, machinery mass and outfit mass, together with the centroid positions of these items. It is appreciated that the use of empirical relationships always involves a certain degree of risk due to the ignorance of the user of the circumstances under which the relationships were derived, such as the type of analysis used, the values of the regression coefficients, and the range of validity of the analysis performed. In the context of the estimation of lightmass characteristics, it was considered that the expressions proposed by Bentley did provide a reasonable estimate of these parameters and were sufficiently accurate to make them suitable for inclusion in the concept design system. It is, however, considered that the provision of a more robust method of estimating the lightmass parameters of a design proposal would be of considerable benefit to the system as a whole. It is also appreciated that the inclusion of a more rigorous estimation procedure at the concept design stage would be quite difficult and would require considerable research effort in its own right. In fact, the estimation of lightmass particulars at this very first stage of the design process could be a problem suitable for solution by an expert system approach.

Another area of the knowledge base which could be improved upon is that concerned with the estimation of powering requirements. This has traditionally been an area fraught with uncertainty and subjectivity, and as such has been the subject of enormous research effort for many years. The procedure utilised in the design system, that

proposed by Holtrop and Mennen, is one of the more recent of the available power estimation techniques. As the method is basically a statistical analysis of existing powering data, the problems associated with the use of empirical relationships as described earlier are equally applicable to this particular powering estimation procedure. It would appear that the resistance estimation component of the procedure does produce reasonable results [7.7] when compared to actual tank-test figures, but appears to be deficient in its conversion from resistance to powering information. It is particularly in this area concerning the determination of propulsive characteristics that the Holtrop and Mennen procedure is found to be rather lacking. In an attempt to rectify these problems, the version of the procedure developed by Marine Design Consultants Limited and utilised here, uses a basis vessel approach to try to improve upon the accuracy of the analysis. This technique does appear to give some improvement over the basic method proposed by Holtrop and Mennen, but is often hindered by the lack of suitable basis vessel data. Due to the lack of basis vessel powering information, this particular feature of the Marine Design Consultants Limited powering procedure is suppressed when being used as part of the containership design system. It is, however, considered that some immediate improvement in the powering components of the design system could be realised if basis vessel data was to be incorporated, thus permitting the aforementioned feature to be utilised. Alternatively, a completely different powering procedure could be utilised in place of the Holtrop and Mennen based procedure, should a suitable one become available.

Apart from the two areas outlined above, it is considered that the knowledge base in its present form provides a remarkably flexible and comprehensive facility for the conceptual design of container carrying vessels.

3.3 Possible future enhancements to the containership design knowledge base.

The two major enhancements which could be made to the containership knowledge base have already been discussed, but there are some further improvements which could be made to the knowledge base without changing the basic methodology or underlying logic to any extent. For example, some improvements could be realised in the advisory/explanatory capabilities of the present knowledge base. These improvements could be made by increasing the number of parameter descriptions contained in the knowledge base, as at present not all of the parameters specified have a

corresponding parameter description.

Although most of the parameter names are self explanatory, the inclusion of a description in the knowledge base for each one of them would obviously increase the explanatory capabilities of the system, especially when being used for the first few times by a particular user.

Ane additional aspect of the concept design system which could be improved upon is the cost model used in the evaluation of proposed loading conditions. It is appreciated by the author that the model currently used is a rather simplistic representation of what is in fact a highly complex problem. For example, the model does not involve directly the first cost of the vessel itself but has this item implicit in the net revenue per container figure. The model is therefore unable to reflect easily the changes in the net revenue per container as caused by variations in the first cost of the vessel resulting from modifications to its specification. Within the current model it is the responsibility of the system user to modify the net revenue figure to reflect changes to the first cost of the vessel.

The above point obviously only applies in cases where the actual physical characteristics of a design proposal have been modified and it is required to obtain a comparison of the potential profitability of alternative proposals. It is envisaged, however, that the present model will only be used to assess the viability of alternative loading conditions on a particular vessel without attempting to change the basic vessel specification. Under these circumstances the current model should enable a quite reasonable measure of the flexibility of a given design proposal to be obtained.

4. Final comments.

This thesis has described the specification and development of a computer aided conceptual ship design system which incorporates expert knowledge. The author considers that the design system developed provides the user with a unique aid for the conceptual design of containerships. The system considers the containership design problem at a level not previously covered by any design system, and it is envisaged that the system will be of considerable assistance to the containership operator as well as to the ship designer. The success of the current project has illustrated the potential gains to be made from the application of expert system based

tools to the solution of ship design problems. It is considered that the success of the current application will encourage the development of other applications for the solution of design problems associated with vessel types such as roll-on roll-off, general cargo, bulk carriers and even naval craft, with some of the logic contained in the present application being used to form the basis of these new systems.

References - Chapter 7

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Computerised hullform and compartmentation sketchpad (CHAS) - worked examples.
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APPENDIX I

Publications Arising from the Work.

1. Hills W., Welsh M.
An effective method of preliminary hullform design using a micro-based workstation.
International Shipbuilding Progress, October 1986.

2. Hills W., Welsh M.
An effective compartmentation method for use in preliminary ship design.
Proceedings of the International Conference on Computer Applications in Shipyard Automation and Ship Design., (ICCAS 88), Shanghai, September 1988.

AN EFFECTIVE METHOD OF PRELIMINARY HULL FORM DESIGN USING A MICRO-BASED WORKSTATION

by

W. Hills* and M. Welsh*

Summary

Recent developments in computing technology and reduced hardware costs have encouraged the use of micro-based CAD workstations. The need for effective design procedures which utilize the attributes of such workstations is recognised. A system for generating a hull form of sufficient accuracy and fairness for use in preliminary design is described. The surface is defined using a set of bi-cubic B-spline surface patches although intermediate forms can be examined via a cubic spline 2-D or 3-D representation. While the mathematical methodology is less sophisticated than that which forms the basis of some of the more advanced systems, fundamental procedures are adapted and structured in a way that ensures accurate and reliable results. This facilitates the rapid generation of hull forms at relatively low cost.

These features provide the designer with a flexible and effective design tool which can be used in an environment where frequent changes may be necessary or a large number of alternative designs have to be examined e.g. at the conceptual or preliminary design stage. An application of the system to the design of a Ro-Ro type form is given.

1. Introduction

The value of any preliminary ship design system is enhanced if it includes a method of rapidly generating a faired hull form. The degree of fairness achieved should be commensurate with the level of design activity. By utilizing the attributes of interactive graphics with automatic curve blending procedures a flexible method of fairing has been devised which allows the fairness of a hull form to be improved as the design is developed. While it is intended for use in preliminary and conceptual design studies the smoothness of the surface can be improved via increased manual involvement. Ideally the form of the vessel should be produced from a minimum of information e.g. from a sketch of the body plan or via an estimate of dimensions and form coefficients. This facility is particularly useful when designing vessels in which the utilization of space and the configuration of the vessel's compartmentation are of primary importance and need to be investigated at a very early stage in the development of a design concept such as a Ro-Ro vessel or passenger ferry. A system which is to be used for such investigation should allow a high degree of user interaction and provide a rapid response, while ensuring the level of accuracy which is normally associated with preliminary design investigation. The time and cost of using the routines should be low hence facilitating exploratory changes is design, which in turn will encourage innovation or creative design.

Recent developments in computing technology together with reduced hardware costs are two of the factors which have encouraged the use of CAD workstations. The increased processing power and capacity of the latest micro-computers has led to adoption of workstations based on relatively cheap micro-computers. The availability of low cost hardware has been accompanied by a parallel increase in the understanding of how to exploit, most effectively, many of the mathematical methods which form the basis of design methodology. One such area of fundamental interest is the representation of a three dimensional shape, such as a ship's hull form, by free-form curved surfaces. Progress in computer graphics, computer aided geometric design and hardware technology has facilitated the development of efficient, cost effective interactive computer aided geometric design systems. This paper describes a micro-based system which is designed for use during the early stages of the ship design process. It facilitates the generation of an accurate definition and data base for use in powering, stability, compartmentation and structural weight investigations.

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2. Overview

2.1. Background

The procedure described in this paper is one element of a comprehensive CAD system being developed in the Department of Naval Architecture and Shipbuilding at the University of Newcastle on behalf of Marine Design Consultants Limited, a subsiduary of British Shipbuilders. This hull form generation module will be integrated with other modules dealing with compartmentation, estimation of volumes and weight, stability and powering.

At an early stage in the project, several requirements were identified which influenced the design and struc-

ture of the system: namely:

i. The role played by the designer when developing a hull form should be similar to that taken when manually developing a form, i.e. the options presented and the related decision making process should have a familiarity about them which makes the user feel comfortable when using the system. In this context it is important that the designer feels that he is in 'control' and is driving the system towards a successful outcome.
ii. Maximum use should be made of the interactive graphics capability although the amount of user involvement should be variable and this flexibility should exist at every stage of the process.
iii. The designer need not understand, or be exposed to, the theoretical concepts of the methods adopted. This theoretical basis should support the generation of a wide variety of hull forms with varying characteristics.
iv. The designer needs to be able to work at different levels of accuracy (and fairness) at each stage in the concept design/tendering/contract design process. This would facilitate the rapid generation of initial forms for examination with subsequent refinement and increased levels of accuracy as the design is developed.
v. The format for data input should ensure that only the minimum of data is handled and the chances of error are minimized.

The main elements of the system which has been designed to meet the above requirements are shown diagrammatically in Figure 1.

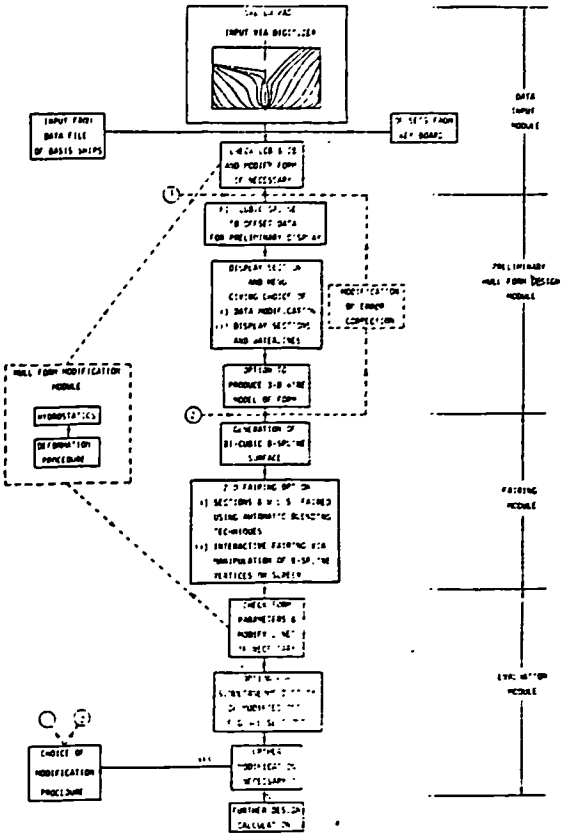

Figure 1. Arrangement of the main modulus of the hull form generation system.

2.2. Description of modules

While a detailed description of the procedures used is given in Section 3, an outline description of the methods used is given in this section to provide an overview and an awareness of the scope of the work covered during the development of the system.

We have drawn heavily on the work of Rogers and Adams [1] while some of the surface description procedures suggested by Cheong [2] have been modified and extended to improve their range of application.

2.2.1. Data format

When writing software for any interactive procedure, it is essential that the structure and format of the data minimises the chances of error, provides a choice where necessary and is consistent with any generally accepted procedures. This latest point is of particular importance when designing a system which is to be used by personnel with differing levels of experience and qualifications. (It is essential that comprehensive, carefully written, user documentation is available).

Three modes of data input are available:

i. Via the digitizer. Offsets can be digitised from a basis body plan or from a sketch body plan of a proposed design. The number of waterlines and sections is variable. An automatic procedure sorts the data and arranges it into the format required by the system.
ii. Direct input of available offsets from the keyboard. This is useful if a good basis hull form is available for which accurate faired offsets are available. Any necessary modification and subsequent fairing can be accomplished rapidly from such a basis.
iii. Direct access to a design offsets file, previously configured, for a basis ship chosen from a data bank of good basis designs. A limited number of basis forms are shown on the screen and the designer is free to select the form which is judged to incorporate those characteristics likely to be desirable in a proposed design.

The data input from any one of these forms is used to determine or confirm the C_B and LCB. If necessary these two parameters can be altered using the method

proposed by Lackenby [3].

2.2.2. Preliminary design stage

At this stage the designer is given the option to view a preliminary set of sections which are represented by cubic splines fitted to the input data, although no attempt is yet made to fair the sections. The aim is to produce a 'sketch' so that a qualitative assessment of the form can be made. The purpose of this display/output is to provide the designer with the opportunity to inspect the general characteristics of the hull form and detect errors before activating the fairing module. It is worth noting that the shape (and smoothness) of the waterlines can be viewed at this stage. The designer can interact with the system to modify the data or form if necessary.

2.2.3. Fairing module

In recent years a great deal of work has been done in the general field of hull form generation and some excellent work has been reported e.g. Reference [8]. Most of this work has been developed for use in large comprehensive, often detailed, design investigations where a high level of accuracy is required. As a result costs can be high when hiring or running such systems. It was apparent that a need existed for a system which included some of the attributes of the more sophisticated systems but was not as rigorous in respect of accuracy, data input and the final measure of fairness. Such a system has wide application in preliminary design where a large number of alternative designs need to be investigated.

Many of the available hull form generation systems incorporate procedures based on Bezier or B-spline curves for surface definition. These curves are defined by the vertices of an open polygon with the shape of a curve being determined by the location of the associated control vertices. Methods based on these curves (and surfaces) allow a high degree of user interaction enabling the shape to be manipulated and 'controlled'. Reference [1] provides a very good introduction to this topic.

After testing several methods, a decision was made to adopt the B-spline basis. This gave the required degree of flexibility and was the least costly in computing terms, although more significantly, it allowed the construction of user kindly system. Further details of the procedures are given in Section 3.4 and a worked example is presented in Section 4.

3. Detailed description of system

As can be seen from Figure 1 the system has been designed on a modular basis with each of the five modules dealing with a particular aspect of the design process. The system is best described in terms of these modules, with an emphasis being given to the measures taken to ensure the integration of each module into the overall design system.

3.1. Hardware configuration

The system has been developed on a micro-based workstation as specififed by British Shipbuilders, with the main components as listed below:

Computer	: IBM PC/AT 20M byte hard disk 1.2M byte floppy disk 360k byte floppy disk
Digitiser	: Calcomp 2000 (350 mm x 350 mm)
Plotter	: Graphtec MP2000 (300 mm x 440 mm)
Graphics screen	: Cambridge PC1024 (510 mm).

3.2. Data input

This module has been structured so as to offer the user alternative methods of data input, thus increasing the flexibility and applicability of the system, as described in general terms in Section 2.2.1. The availability of a suitable basis ship in a data bank can allow the user to rapidly generate a hull form to suit the design requirements. The only input required are the design vessel principal dimensions, and form characteristics, particularly C_B and *LCB*. The design vessel hull form is generated via the basis hull form data bank and the hull form modification module which is described later. Despite allowing rapid data generation, this method is restrictive in that it is totally dependent on the quality and scope of the data bank of basis vessels.

Of the three alternatives the most time consuming method of input is that in which waterline or section offsets are input to a datafile via the computer keyboard. Not only is this method time consuming (depending on the number of data points) but it is also prone to typing errors. The method is also restrictive in that preliminary offset data may not be available for the design vessel and the form will need to be modified before fairing.

The final option which overcomes the difficulties associated with the two methods described above, involves the use of a sketch body plan for the design vessel. These preliminary body sections can be rapidly converted into numerical waterline offsets via a digitising tablet for use in the later stages of the design development. This method of input is particularly suitable for novel design development and is restricted only by the creativity of the designer and his ability to sketch sections which are a reasonable indication of

3-D shape.

3.3. Preliminary hull form design

This stage of the design development is independent of the method of data input which has been used. The system utilises a menu driven approach with the various options available to the designer being displayed on the graphics screen. The use of menu driven software allows the designer to develop a hull form on the graphics screen once he has created the initial datafile using one of the methods described in Section 3.2. This module facilitates the automatic generation of intermediate transverse sections at any position along the length of the vessel by using a 3-D polynomial interpolation algorithm. Similarly waterlines can be generated and displayed at any required height above the baseline, permitting a preliminary check on the fairness of the sectional data and the deck outline or plan view. The display of section and waterlines on the Cambridge PC1024 graphics screen is achieved with the use of piecewise cubic splines. The piecewise cubic spline is a series of polynomial segments spanning only two points. A single parametric cubic spline is given by:

$$P(t) = \sum_{i=1}^{4} a_i t^{i-1} \qquad t_1 \leq t \leq t_2$$

i.e. $P(t) = a_1 + a_2 t + a_3 t^2 + a_4 t^3$

where $P(t)$ is the position vector of any point on the curve.

By applying the conditions of continuity of position, slope and curvature across the joints of neighbouring spline segments, a continuous cubic spline is achieved passing through each of the input data points.

The speed at which cubic splines can be generated makes them ideal for use at this stage of the design development, where a high level of user interaction is not required. The software allows the user to delete or re-position data points in order to remove errors or unwanted points of inflexion.

3.4. Fairing module

At this stage the data exists in the form of waterline offsets at a number of transverse sections along the ships hull, i.e. in a format familiar to all ship designers. The data is then used to generate the control vertices of the associated B-spline surface for the hull form.

3.4.1. B-spline curves and surfaces

The B-spline curve is similar to the Bezier curve in that it is associated with the vertices of a polygon. Unlike the Bezier curve however, the B-spline basis is non-global since each vertex is associated with an unique basis function and only affects the shape of the curve over the region where the associated basis function is non zero. Further, the order of the B-spline can be selected independently of the number of vertices in the defining polygon. The B-spline curve is given by:

$$P(t) = \sum_{i=0}^{N} V_i N_{i,k}(t) \qquad 0 < t \leq t_{max}$$

where $P(t)$ are the position vectors along the curve,

V_i are the $n+1$ polygon vertices,
k is the order of the curve.

The weighting function $N_{i,k}(t)$ is defined by:

$$N_{i,1}(t) = \begin{cases} 1 \text{ for } X_i \leq t < X_{i+1} \\ 0 \text{ otherwise} \end{cases}$$

and

$$N_{i,k}(t) = \frac{(t - X_i) N_{i,k-1}(t)}{X_{i+k-1} - X_i} + \frac{(X_{i+k} - t) N_{i+1,k-1}(t)}{X_{i+k} - X_{i+1}}$$

where the X_i are elements of a knot vector. A more complete account of the B-spline theory can be found in References [4] and [5]. The characteristics of B-spline curves are applied to B-spline surfaces, providing a powerful tool for surface design.

In order to extend the B-spline theory to surfaces, it is advantageous to constrain some of the degrees of freedom associated with B-splines. Restricting the degree of the curve to three produces a bi-cubic B-spline surface as discussed by Barsky and Greenberg [6]. The surface is considered to consist of a mosaic of surface patches, each one being cubic in each of its parametric directions and possessing first and second order continuity in both directions. Each of the surface patches is controlled by 16 control vertices and is independent of all other vertices. Conversely a given vertex exerts influence over only 16 surface patches and has no effect on the remaining patches. This means that the effects of moving a control vertex are limited to 16 patches. A point on the (i, j)th uniform bi-cubic B-spline surface patch is a weighted average of the 16 vertices $V_{i+r,j+s}$ $r = -2, -1, 0, 1$ and $s = -2, -1, 0, 1$. The mathematical formulation for the patch $Q_{ij}(u, v)$ is then:

$$Q_{ij}(u, v) = \sum_{r=-2}^{1} \sum_{s=-2}^{1} bb_{rs}(u, v) V_{i+r,j+s} \qquad \text{for } 0 \leq u, v \leq 1$$

The set of bivariate uniform basis functions is the tensor product of the set of univariate basis functions. That is:

$$bb_{rs}(u, v) = b_r(u) b_s(v) \quad \text{for } r = -2, -1, 0, 1 \quad s = -2, -1, 0, 1$$

The formulation for the patch $Q_{ij}(u, v)$ can be rewrit-

ten as:

$$Q_{ij}(u,v) = \sum_{r=-2}^{1} \sum_{s=-2}^{1} b_r(u)\, V_{i+r,j+s}\, b_s(v)$$
$$\text{for } 0 < u, v \leq 1$$

where the B-spline basis functions are given by:

$$[b_{-2}(u), b_{-1}(u), b_0(u), b_1(u)] =$$
$$= [u^3 u^2 u\ 1]\frac{1}{6}\begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 0 & 3 & 0 \\ 1 & 4 & 1 & 0 \end{bmatrix}$$

In practice the surface control vertices are the unknowns to be determined while the knowns are the input waterline offsets (P_{ij}). For each of these offset points an equation can be derived in terms of the associated control vertices. The method used to determine the surface control vertices has been adapted from the work of Cheong [2] which utilises the procedure outlined by Barsky and Greenberg [6]. A flow diagram for the procedure is given in Figure 2.

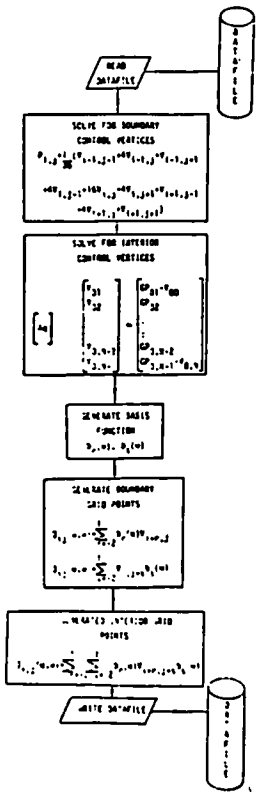

Figure 2. Flowchart for program Bsurf.

Although the B-spline surface provides the designer with an extremely powerful tool for hull form development, it can be very difficult for someone familiar with the usual methods of hull fairing using two dimensional views to relate to a three dimensional surface. This difficulty is reduced by presenting the B-spline surface in a more familiar two dimensional format. Transverse hull sections and waterlines can be displayed on the graphics screen together with their associated surface control vertices. The control vertices have the effect of magnifying any error in the data thus enabling bumps, hollows and flats to be detected more easily. The whole fairing process is related to the manipulation of these control vertices, to produce a smooth surface, either by automatic or manual methods. The task of moving the vertices manually i.e. by selecting new co-ordinates, can be time consuming. As a primary aim in the development of the system was to provide a means of the rapid generation of hull forms, it was decided to include an automatic method of surface smoothing which required no user interaction. The technique selected for the task after a comparison with a least squares method was that of parabolic blending (Reference [7]).

Parabolic blending involves the generation of two separate parabolic curve segments each defined by

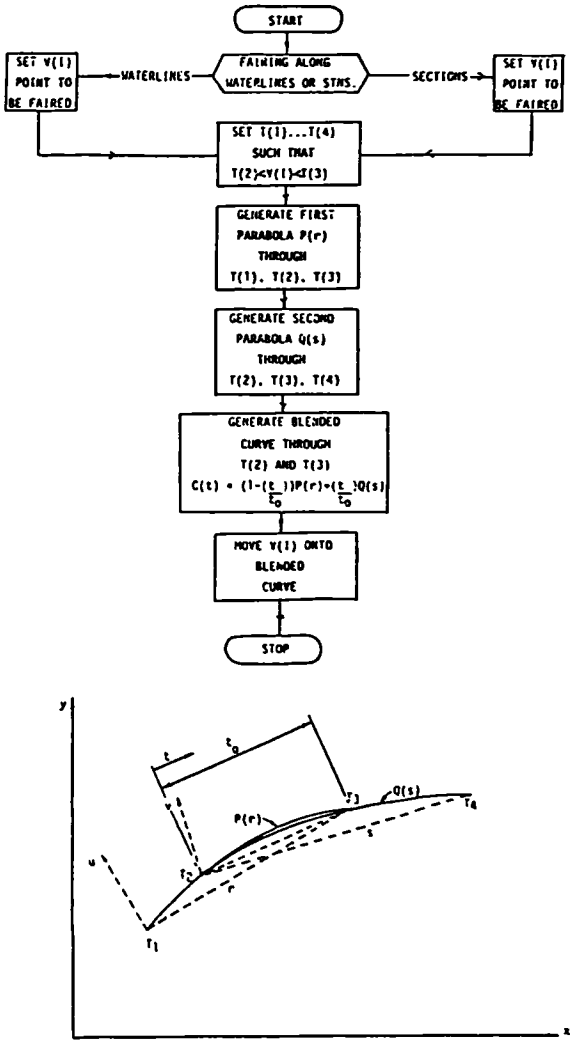

Figure 3. Parabolic blending algoritm.

three points. Each of these segments has a common span over which a blended curve is generated. If it is assumed that this blended curve contains the correct location for an erroneous vertex, then the relevant vertex can be moved to coincide with the curve. This technique provides a means of rapidly smoothing the hull in both the vertical and horizontal planes with no input from the system user. A flow diagram is given in Figure 3.

If the hull form is to incorporate special features such as chines and knuckles then these can be controlled by means of manual manipulation of the vertives. For example the specification of three vertices at a single point will produce a knuckle as shown in Figure 4. In this way a hull form can be developed which posses a variety of required local features.

By using a combination of the automatic vertex blending and manual manipulation techniques, a reasonably fair hull form can be developed in a fraction of the time taken by the traditional manual method. For convenience the system is at present structured to facilitate fairing between the perpendiculars however it can be modified to include the ends of the vessel.

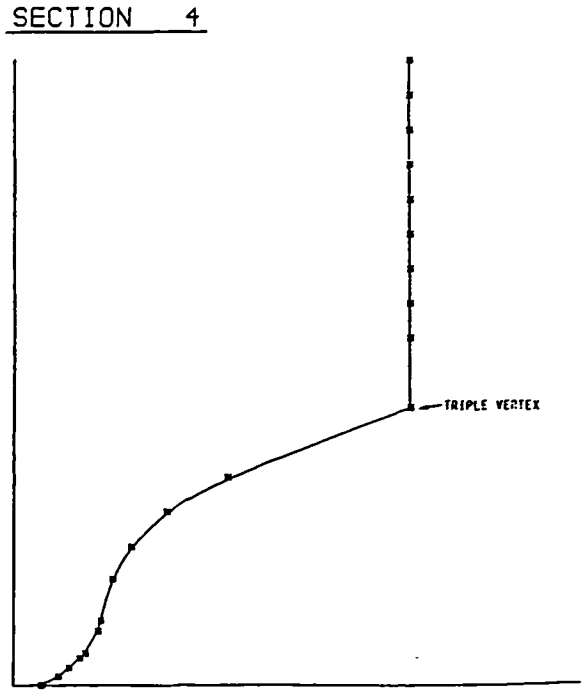

Figure 4.

3.5. Evaluation module

This stage of the design development is critical as it involves the evaluation of the effects of changes made to the hull form during the fairing process. Further use is made of the routines contained in the hull form modification module to determine the design vessel form characteristics and to further modify the design if necessary in order to meet the specified design requirements.

Once the user has completed the evaluation of the design hull form he is presented with the option to repeat the whole process if substantial modifications are required. If the design is considered promising a reasonably fair hull form with the required hull characteristics and a full set of hydrostatic particulars will be available for the vessel together with all the necessary data for subsequent stages of the design process.

3.6. Hull form modification module

This module is called upon a number of times in the system and consists simply of routines to determine the hydrostatic particulars of the vessel together with a procedure based on Reference [3] for the deformation of the design hull form. This ensures that the requirements regarding the specified values of C_B, C_p and *LCB* are satisfied.

4. Worked example

The attributes of the system can be illustrated by describing the development of a 'faired' hull form for a Ro-Ro vessel. A first estimate of the vessel's dimensions is assumed. The block coefficient of the design is to be 0.6223 with an *LCB* of 63.0 metres forward of the aft perpendicular i.e. 3.6%*L* aft of midships. A preliminary study suggests a bulbous bow will be advantageous and a chine in the upper part of the aft body section will provide a wide deck area and assist operational efficiency.

4.1. The hull form design procedure

In this instance basis vessel data was not available and the starting point for the design process was a sketch body plan incorporating the required features based on typical Ro-Ro sections, Figure 5. It is worth noting that the designer has complete freedom in the choice of form, including section shape, although these may be modified as fairing takes place and as any necessary deformation is made to achieve the specified C_B and position of *LCB*.

The section offsets were input via the digitiser. No restrictions are placed on the format of the data required. The user can vary the number of points used to define sections as curvature changes. Obviously in areas of high curvature e.g. towards the ends, a better definition of sections is achieved by increasing the number of data points. Sections which are repeated, such as those in the parallel middle body can be entered by invoking the 'copy option' so that identical sections are generated at specified points along the ves-

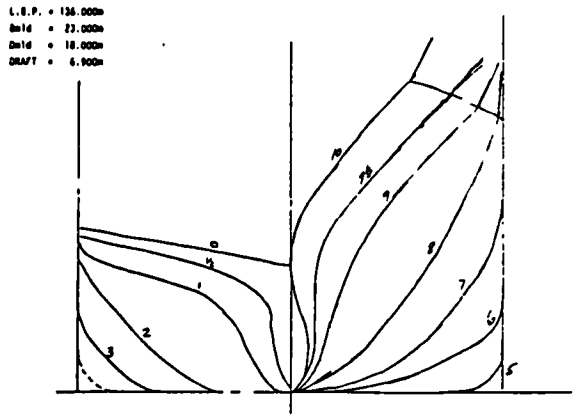

Figure 5. Sketch body plan (case 1) (not to scale).

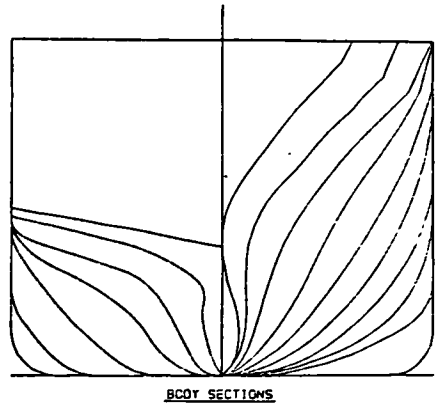

Figure 6. Cubic spline fit of input and interpolated sections.

sel. Using the 3-D polynomial interpolation procedure intermediate sections can be generated.

The C_B and *LCB* are checked at this stage and modified if necessary. Calculations from the input data gave;

BLOCK COEFFICIENT = 0.6058
LONGL. CENTRE OF BUOYANCY = 63.2 m fwd AP

The hull form deformation module was activated to give the required values of

BLOCK COEFFICIENT = 0.6223
LONGL. CENTRE OF BUOYANCY = 63.0 m fwd AP

A first plot of the body plan (unfaired) of the design sections is produced using cubic splines, Figure 6. The time required to produce this form, which incorporates the speficied design features and form characteristics, from the initial concept sketch is under 10 minutes.

4.2. B-spline surface generation

Assuming a qualitative assessment of the first plot confirms that no major alterations are necessary, the data is used directly as input into the surface generation procedure which produces the control vertices for the B-spline surface. The automatic generation of the control vertices facilitates the fairing of the surface. Some processing of the vertex data is carried out to remove unwanted undulations on the surface, especially in areas of zero offset, as shown in Figures 7a and 7b.

4.3. Surface fairing

Smoothing of the surface is achieved by application of the automatic parabolic blending technique to the surface control vertices in both the vertical and horizontal planes. This technique is particularly powerful and allows a smooth hull form (sections and waterlines) to be developed in 3-4 minutes. As the design vessel is to have a knuckle in the aft body, it is neces-

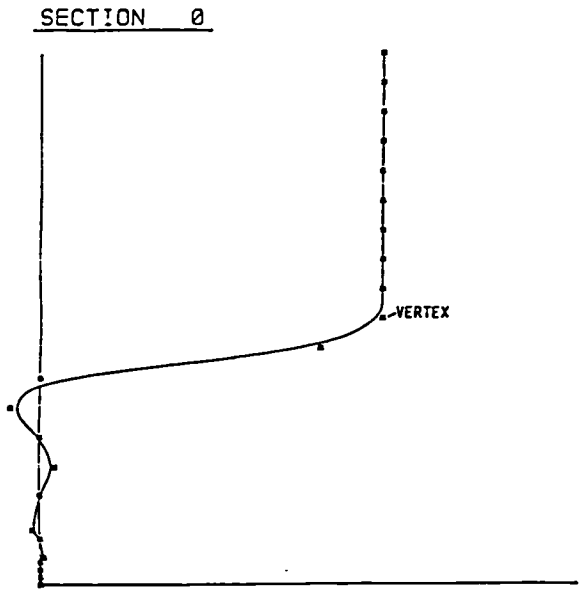

Figure 7a. Arrangement of vertices before fairing.

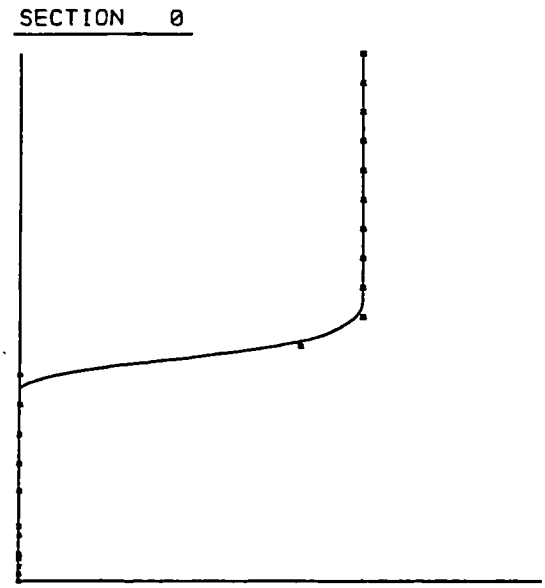

Figure 7b. Arrangement of vertices after fairing.

sary to introduce this feature by manual manipulation of the control vertices as shown in Figure 4.

At all stages of the surface fairing use is made of an option which allows modified and original sections and waterlines to be displayed simultaneously for inspection before the modifications are accepted and confirmed. This combination of manual and automatic fairing allows the rapid development of faired hull forms incorporating special features.

As a final option the designer can then update this data to re-generate the B-spline surface giving additional or re-spaced sections as required, see Figure 8, together with a 3-D plot of the surface, Figure 9. One last check of the hydrostatic particulars and form coefficients is made to ensure compliance with the specified values. The whole process from the designers initial sketch through to the final faired form took approximately 20 minutes for the design shown.

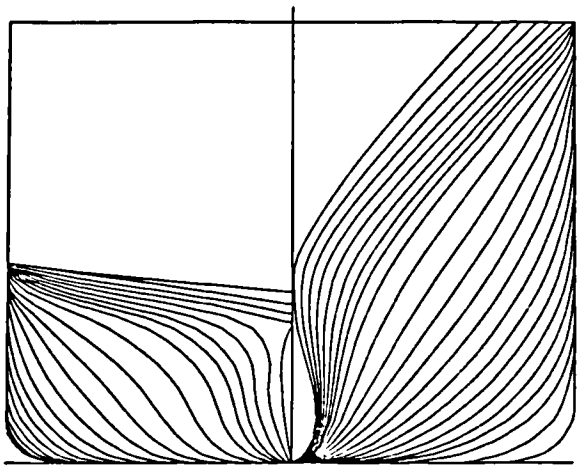

Figure 8. Final body sections derived from B-spline surface.

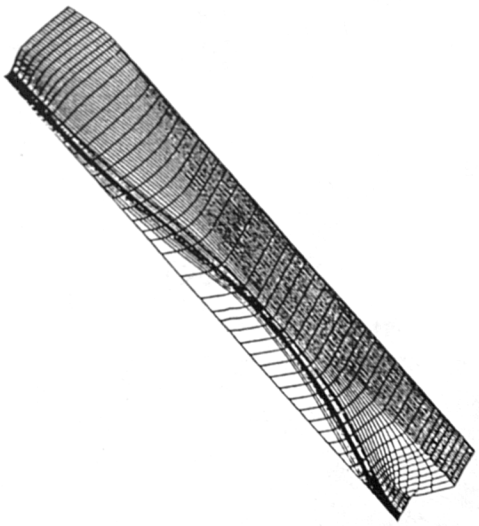

Figure 9. 3-D plot of final B-spline surface.

5. Concluding remarks

A system has been described which allows the rapid generation of a faired hull form which is of sufficient accuracy for use in preliminary ship design. It will be especially useful in organisations which deal with a large number of enquiries and tenders. By providing a series of options to the designer the flexibility of the system is enhanced and the quality of the definition can be selected to match the level design activity. In this way a firm base is established which provides data suitable for input to procedures for examining stability, capacity, compartmentation, powering, structural layout and weight. The emphasis placed on producing a user friendly system, utilizing procedures which appear familiar to a wide range of personnel ensures that hull forms can be developed in an efficient and effective manner.

Acknowledgements

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Computer Applications in the Automation of Shipyard Operation and ship Design VI
Lin Dingyi, Wang Zhengda and Chengi Kuo (Eds.)

AN EFFICIENT COMPARTMENTATION METHOD FOR USE IN PRELIMINARY SHIP DESIGN

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The effectiveness of a preliminary or concept design investigation is considerably enhanced if efficient methods of layout definition and compartmentation are available. A method is described which is useful during the early stages of the design process when it is often necessary to generate and examine large numbers of alternative designs in a limited time. The method is user friendly and highly interactive. These features encourage the examination of alternative proposals which in turn can lead to innovation.

The starting point in the management of space is the generation of a hull form. The procedure described utilizes cubic splines and bi-cubic B-spline surfaces as part of a "multi-level" hull form generation procedure which includes parabolic blending as an aid to fairing.

The internal layout of a ship is defined as a set of geometric primitives and the layout development procedure utilizes interactive graphics. Examples are given which illustrate boundary manipulation and describe the associated active database.

An illustrative example is given showing the application of the method to the design of a Ro-Ro vessel layout.

1. INTRODUCTION

For many ship types the primary design consideration is the efficient utilization of available space. Efficiency in this context usually implies an arrangement of space which ensures the effective operation of the ship. This depends upon the correct placement of any individual space and the most effective interrelationship between all spaces.

Not only can good space management procedures enhance the functionality of a vessel but it can lead to reduced first costs. If overall area or volumetric requirements can be reduced it may be possible to attain the same level of operational capability with a smaller vessel. Other savings may be made by incorporating procedures which allow optimal routing of services which facilitate the minimisation of installation costs.

Layout design in ships is usually considered via a hierarchial approach:

i) Main zone and boundary definition to satisfy some overall functional requirements such as cargo subdivision, weapon disposition etc.

ii) The arrangement and disposition of areas and compartments in a way which optimises their contribution to overall ship efficiency in operation.

iii) System layout design, especially based on procedures which attempt to optimise system routing subject to physical constraints imposed by (i) and (ii) above.

While usually considered separately, all three levels of activity are interrelated and decisions are influenced by environmental and habitability considerations. Many of the criteria used to reflect these factors are subjective and difficult to quantify. They may impose conflicting demands upon the design and individual designers will have differing opinions of their relative importance when considering their contribution to the criterion of performance used to compare alternative designs. Hills and Cort [1] suggest an approach to solving layout design problems involving multi-objective criteria based on 'fuzzy' logic.

Functional arrangement design and subsequent

compartmentation procedures are enhanced if an efficient method is available for defining the main ship zones and boundaries. The availability of relatively inexpensive CAD workstations with powerful interactive graphics facilities provide the designer with an ideal design aid for solving problems in which space manipulation and organisation in 3-D is the primary objective.

Ship layout design is an integral part of the overall design process and it is essential that the data structure permits interraction to take place with other related design activities such as hull form design and structural design.

The method described is this paper has been developed with the above points in mind. It is particularly useful during the concept or preliminary design stages where a large number of alternatives need to be examined.

2. OVERVIEW

2.1 Background

The methods described in this paper are concerned with ship layout design and compartmentation. These topics represent two facets of an integrated design system being developed at the University of Newcastle as part of a British Shipbuilders funded research programme. The other modules are shown in Fig. (1). Current work is concerned with modules for work content estimation and design for production.

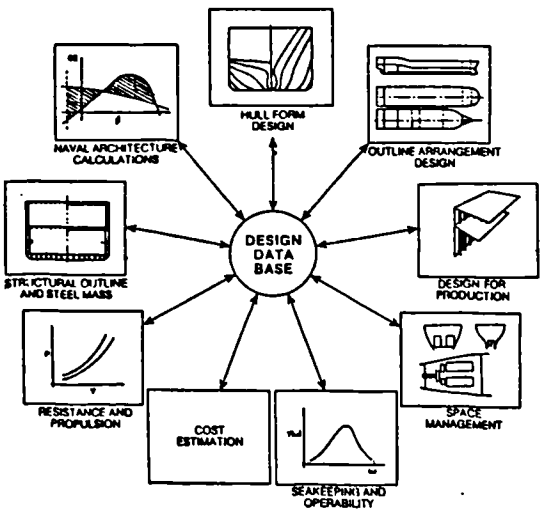

Fig.1 Integrated Ship Design System

2.2 General Arrangement Design

The design of the general arrangement is perhaps the most important activity when developing a new design concept. Decisions taken at this stage have a far reaching effect on the outcome of the investigation. The general arrangement has a considerable effect on the economics of the vessel, its functionality and its producibility.

Depending on the type of vessel under consideration, several criteria have to be considered as having a direct bearing on the layout of the general arrangement, ie.

* Type and quantity of cargo to be carried,
* Operational profile - speed, round trip distance, number of ports.
* Cargo handling equipment and access equipment.
* Safety - regulatory bodies.
* Strength - classification societies.
* Functionality - including the shipboard environment.

A number of systems have been developed which rely on the iterative approach to general arrangement design with most effort being in the area of warship design [2], [3].

The task of defining all of the required spaces is a difficult one. Space can be considered in many different forms; it can be thought of as an actual required volume, length, height or perhaps more importantly in certain ship types, deck area. As well as requirements regarding the amount of space needed there will inevitably be restrictions on the acceptable shapes and locations of individual compartments.

For any one design there will be a large number of alternatives which satisfy the given requirements. Practical ship layout design involves the indentification and application of constraints to reduce the number of possible alternative solutions. The remaining solutions can be examined and a decision made as to which one is to be adopted for further development.

The iterative nature of layout development suggests that an interactive approach should be adopted to enable the designer to apply his experience and skill when specifying an internal arrangement. Feedback will inform the designer of the properties of that layout, and alterations can be made which are necessary to improve the quality of the proposal.

2.3 Interactive Layout Design

Several interactive systems have been developed for ship layout design especially in the area of naval work. All of these systems require the designer to have a fairly detailed knowledge of the proposed layout before he can commence the definition. These systems allow a high degree of layout definition with the facility to define hundreds of individual compartments. This level of definition is obviously necessary in the development of warship designs, but is not considered to be a requirement of a layout definition system intended for use at the pre-contract design stage of merchant vessels where the main concern is the provision of adequate cargo spaces for the profitable and safe operation of the vessel.

Nehrling [4] developed a method for ship general arrangement design which was based on the use of simple patterns to build up a complete representation of an arrangement. He proposed that even the most complex of internal arrangements could be formed by the superposition of these basic patterns. Whilst appearing to be very flexible, this method assumes that the designer has a detailed knowledge of the proposed arrangement before he starts the definition. The method is also restrictive in that the designer is required to use standard patterns which may not always match his requirements although

Nehrling does state that his system allows the library of patterns to be extended to suit particular requirements. Perhaps the most important shortcoming of the pattern approach is the fact that the layout is simply a collection of adjoining compartments and no significance is attached to the boundaries of these compartments. Hence the layout as defined is not used in the design process to define structural arrangements, or to determine mass estimates.

Since the layout design module of the preliminary design system being described is intended to provide data for structural arrangement and mass estimation procedures, it was considered necessary to adopt an approach which enabled some physical significance to be attached to the individual compartment boundaries. This created the need for an appropriate hull form generation procedure.

3. HULL FORM GENERATION

Having defined an initial estimate of the dimensions and form coefficients of the hull, the shape of the form, including the above water part, can be decided. An effective way of developing a hull form is to use a method of incorporating interactive graphics. The definition of the hull envelope is the basis of all space layout design procedures. It facilitates the generation of a data base of offsets which can be used in the definition of compartments and boundaries of space. Given the processing power of the latest CAD/CAM systems together with progress made in developing effective methods of generating a hull form definition [5] the time taken to produce a form at a level of accuracy commensurate with the preliminary or concept design is measured in minutes. Thus the designer is able to examine a range of alternative forms before deciding which will be used as the basis for the layout design procedure.

3.1 The Hull Form Design Procedure

The method used to generate a hull form is described fully in [5]. However since it forms the basis of the compartmentation and layout procedure some details of the design procedure are given.

A diagram showing the main modules of the hull form generation procedure is shown in Fig.(2). To demonstrate the application of the method a form for a Ro-Ro vessel is developed. In this case basis vessel data was not available and the starting point for the design process is a sketch body plan incorporating the required features based on typical Ro-Ro sections, Fig.(3). It is worth noting that the designer has complete freedom in the choice of form, including section shape, although these may be modified as fairing takes place and as any necessary deformation is made to achieve the specified block coefficient and position of longitudinal centre of buoyancy.

The section offsets are input via a digitiser. No restrictions are placed on the format of the data required. The user can vary the number of points used to define sections as curvature changes. Obviously in areas of high curvature, e.g. towards the ends, a better definition of sections is achieved by increasing the number of data points. Using a 3-D polynomial interpolation procedure intermediate sections can be generated. The C_B and LCB are checked at this stage and modified if necessary.

A first plot of the body plan (unfaired) of the design sections is produced using cubic splines, Fig(4). The time required to produce this form, which incorporates the specified design features and form characteristics, from the initial concept sketch is under 10 minutes.

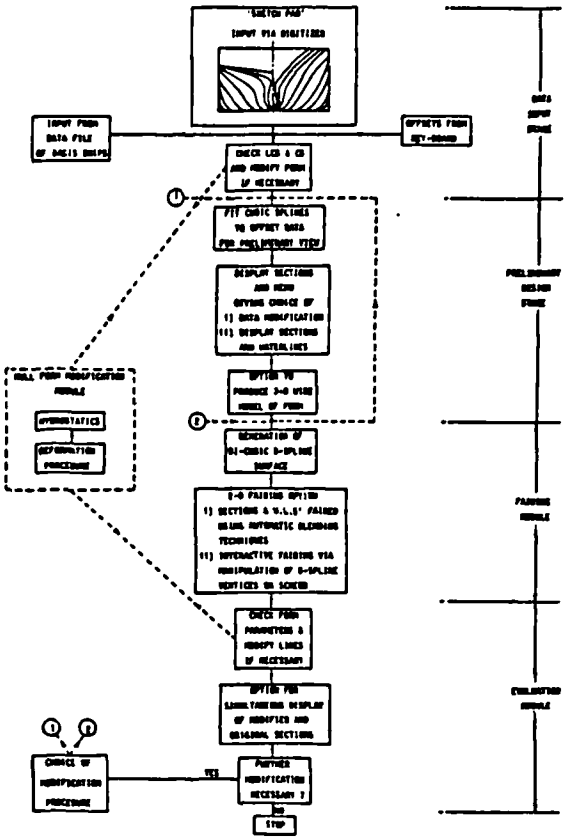

Fig.2 Arrangement of the main elements of the Hull form generation module

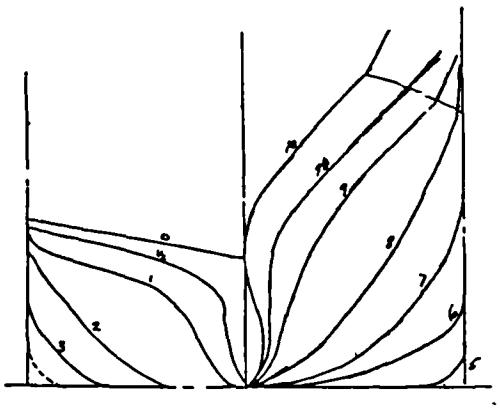

Fig.3 Sketch body sections to be digitized.

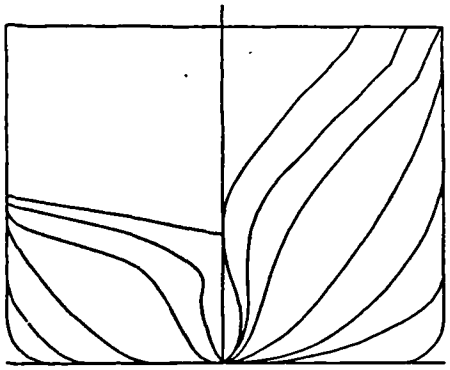

Fig.4 Cubic spline fit of digitized hull form

3.2 B-Spline surface generation

Assuming a qualitative assessment of the first plot confirms that no major alterations are necessary, the data is used directly as input into the surface generation procedure which produced the control vertices for the B-spline surface. The method used to determine the surface control vertices utilises the procedure outlined by Barsky and Greenberg [6].

Although the B-spline surface provides the designer with an extremely powerful tool for hull form development, it can be very difficult for someone familiar with the usual methods of hull fairing using two dimensional views to relate to a three dimensional surface. This difficulty is reduced by presenting the B-spline surface in a more familiar two dimensional format. Transverse hull sections and waterlines can be displayed on the graphics screen together with their associated surface control vertices. The control vertices have the effect of magnifying any error in the data thus enabling bumps, hollows and flats to be detected more easily. The whole fairing process is related to the manipulation of these control vertices, to produce a smooth surface, either by automatic or manual methods. The task of moving the vertices manually i.e. by selecting new co-ordinates, can be time consuming. As a primary aim in the development of the system was to provide a means of the rapid generation of hull forms, it was decided to include an automatic method of surface smoothing which required no user interaction. The technique selected for the task after a comparison with a least squares method was that of parabolic blending [7].

3.2.1 Parabolic Blending

Parabolic blending involves the generation of two separate parabolic curve segments has a common span over which a blended curve is generated. If it is assumed that this blended curve contains the correct location for an erroneous vertex, then the relevant vertex can be moved to coincide with the curve. This technique provides a means of rapidly smoothing the hull in both the vertical and horizontal planes with no input from the system user. A flow diagram is given in Fig.(5).

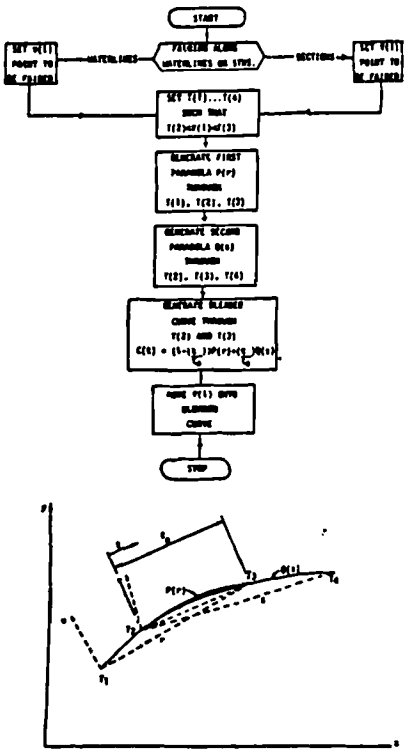

Fig.5 · Flowchart of parabolic blending algorithm

If the hull form is to incorporate special features such as chines and knuckles then these can be controlled by means of manual manipulation of the vertices at a single point. In this way a hull form can be developed which possess a variety of required local features.

By using a combination of the automatic vertex blending and manual manipulation techniques, a reasonably fair hull form can be developed in a fraction of the time taken by the traditional manual method.

3.3 Surface Fairing

Smoothing of the surface is achieved by application of the automatic parabolic blending technique to the surface control vertices in both the vertical and horizontal planes. This technique is particularly powerful and allows a smooth hull form (sections and waterlines) to be developed in 3-4 minutes. As the design vessel is to have a knuckle in the aft body, it is necessary to introduce this feature by manual manipulation of the control vertices.

At all stages of the surface fairing use is made of an option which allows modified and original sections and waterlines to be displayed simultaneously for inspection before the modifications are accepted and confirmed. This combination of manual and automatic fairing allows the rapid development of faired hull forms incorporating special features.

As a final option the designer can then update this data to re-generate the B-spline surface giving additional or re-spaced sections as required, see Fig. (6), together with a 3-D plot of the surface, Fig.(7). One last check of the hydrostatic particulars and form coefficients is made to ensure compliance with the specified values. The whole process from the designers initial sketch through to the final faired form takes approximately 20 minutes.

Having created the hull form the designer can now proceed to layout space within the hull envelope.

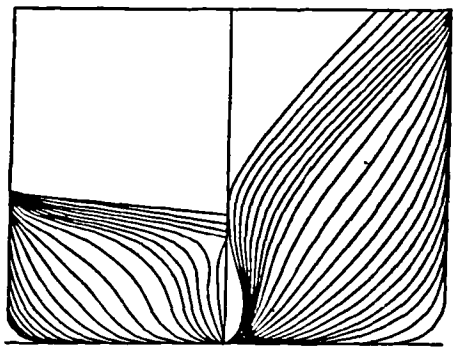

Fig.6 Plot of interpolated body sections

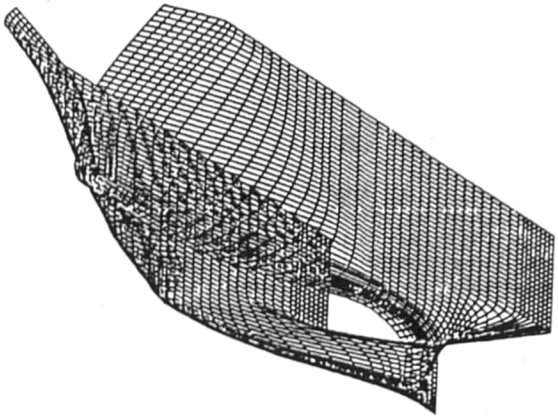

Fig.7 Isometric view of hull form

4. LAYOUT AND COMPARTMENT DEFINITION

To meet the requirements outlined in the previous section,the general arrangement design process can be considered as comprising two distinct but related stages, layout definition and compartment definition.

4.1 Layout Definition

Any vessel type is built up from structural elements which provide for its strength and the ability to carry cargo (or passengers) safely. The layout definition process can be considered as the process of deciding on the disposition of these structural elements within the confines of the defined hull form. The structural elements can be expressed in a hierachial form as shown in Fig.(8).

The tertiary and, to a large extent, the secondary levels of structural elements are considered at the structural design stage of the design process as these are governed by Classification Society requirements relating to detailed structural design and scantling determination.

The layout definition process is mainly concerned with the primary level of structural elements such as decks, flats, bulkheads, inner hulls etc, and also some secondary elements such as watertight/oiltight girders and floors in double bottom areas where these form the boundaries of individual compartments. Once the arrangement of these elements has been decided upon, it is unlikely that they will be changed at the structural design stage

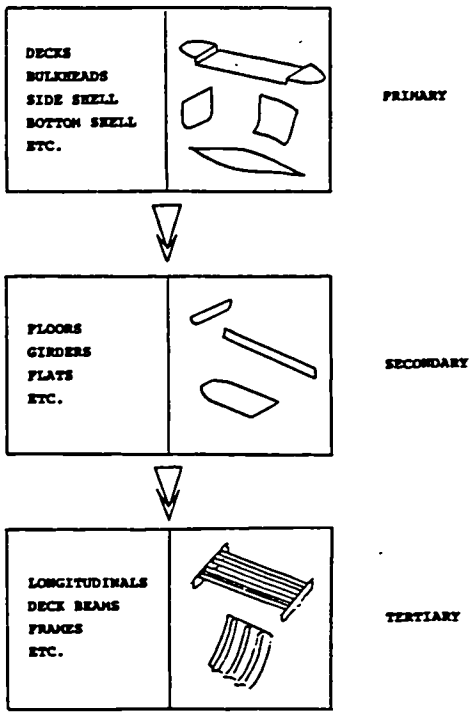

Fig.8 Structural element hierarchy

where design modifications are normally restricted to the variation of frame or longitudinal spacing in an attempt to reduce weight/cost [8].

The layout definition module of the preliminary design system provides the designer with the means to build up any internal arrangement using representations of the primary structural elements, thus enabling a direct link with a procedure for detailed structural arrangement and compartment definition to be described later.

4.1.1 Boundary Elements

The problem of defining an internal arrangement can be reduced to one of manipulating geometry primitives so that they provide a realistic representation of the major internal structural boundaries of actual vessel types. Examination of various merchant vessel type general arrangements indicates that any internal arrangement can be considered as comprising a relatively small number of basic geometric elements which represent the various structural

boundaries found in a wide variety of ship types. The basic geometric elements identified for inclusion in the layout definition procedure and examples of their equivalent structural boundaries are as shown in Fig. [9].

The layout definition routines enable the designer to develop an internal arrangement using the boundary representations described above. As the aim throughout the development of the system is to provide the user with an extremely flexible and user-friendly preliminary design tool,the internal arrangement of a vessel can be defined using a combination of three procedures,

i) interactive keyboard definition,
ii) interactive sketch definition,
iii) free-hand definition.

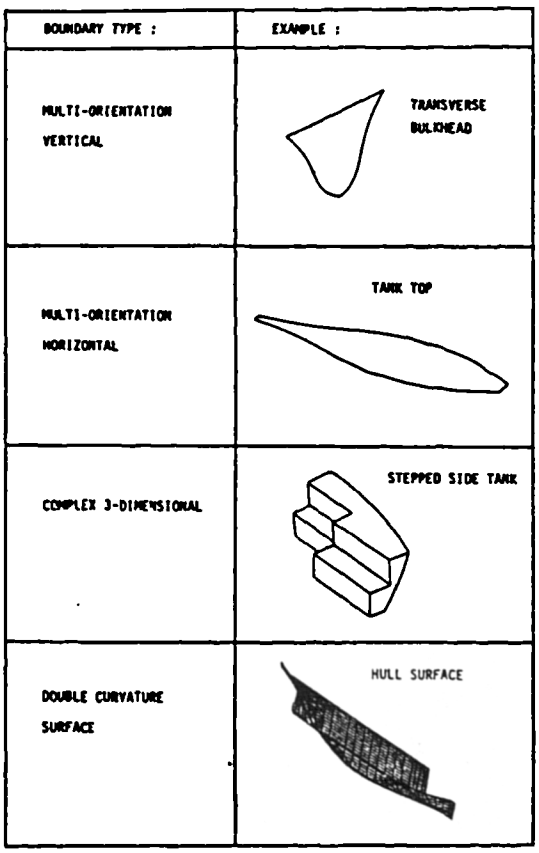

Fig.9 Boundary Types

4.1.2 Interactive Keyboard Definition

This mode of definition enables the designer to create a representation of a layout by typing relevant commands from the computer keyboard. These commands define the location and extent of the various structural boundaries which make up the general arrangement.

This method of input is ideal if the user has knowledge of the desired layout, i.e. when the exact position of decks, bulkheads etc. is known.

4.1.3 Interactive Sketch Definition

This mode allows the designer to define an internal arrangement from a sketch of the design profile and deck plan. The definition is achieved by digitization of the locations of the various structural boundaries from sketches via the digitizer tablet. The sketch general arrangement can be obtained from a variety of sources such as a technical data sheet, or more importantly, can be the designer's own interpretation of a conceptual layout.

4.1.4 Free-hand Definition

This method of definition allows the designer to build up an arrangement interactively on the graphics screen by using the digitizer mouse to indicate the location of decks, bulkheads etc. on a profile of the vessel displayed on the screen.
Menu options are provided for the insertion, deletion, and manipulation of these boundaries on both profile and plan views of the vessel. Other options, when selected, result in the display of the outlines of selected decks and bulkheads together with their associated physical properties such as enclosed area, centroid location, critical dimensions etc.

A required layout can be defined either by the exclusive use of only one of the options described above, or by using a combination of the available input options.

The definition procedures provided, allow a realistic representation of a vessel's internal arrangement to be developed in a very short time, e.g. the layout shown in Fig.(10) was developed in about 30 minutes using the free-hand definition mode.

4.1.5 Boundary Relationships

An examination of a ship general arrangement will reveal a number of basic geometric relationships between the various structural boundaries which could be utilised to the benefit of the designer when developing a new internal layout.

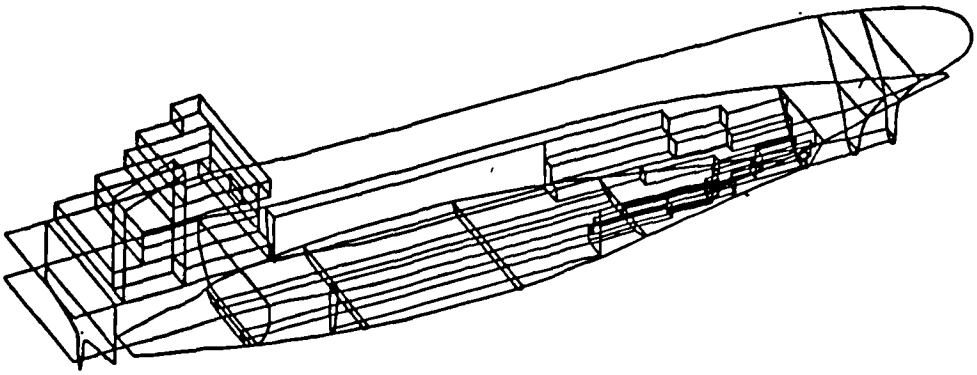

Fig.10 Isometric of defined layout

The most obvious relationships exist between those boundaries which coincide with the termination of other boundaries such as deck/bulkhead intersections as illustrated in Fig.(11). The recognition of such relationships and their incorporation into the layout definition procedures considerably reduces the time required to modify an arrangement and facilitates the rapid evaluation of alternative internal configurations. The system has a built in "intelligence" which allows it to recognise basic relationships between the various boundary elements with the result that changes made to individual boundaries are automatically reflected by modifications to the positions or extent of associated elements. Fig.(12) shows the overall effect on a given layout of the user changing the location of a single boundary element, illustrating the way in which knowledge of physical relationships can be used to assist the system user develop an internal arrangement.

4.2 Definition of Erections

The basic boundary representations described above can be used to produce a model of the internal arrangement of a wide variety of vessel types. This approach is extended to allow the definition of erections above the main hull envelope, eg. accommodation, forecastle, funnels etc.

In order to speed up the definition of an erection layout, the system provides the user with various menu options which allow individual erections to be moved and copied to different locations on the vessel or to be removed from it altogether.

By combining the erection representation with that of the internal arrangement, a full picture of the proposed general arrangement of the design vessel can be obtained. The graphics capabilities of the system are again utilised to enable the user to obtain a visual representation of the defined arrangement both on the graphics display and in hardcopy form. This graphical representation is essential for the detection of boundaries which are incorrectly located or surplus to requirements, and to detect interference between individual boundary elements. The rotation, windowing and translation capabilities of the graphical routines enable the representation to be viewed from any aspect.

4.3. Layout Deformation

The ability to modify individual elements of a defined general layout is an essential part of any procedure which is intended to provide the designer with a flexible tool for general arrangement design. Similarly, the ability to deform the layout and replace complete groups of boundary elements is considered necessary to increase the speed and versatility of the system and enhance its usefulness to the designer. Such a capability demanded a unique approach to the layout definition data handling process and resulted in the adoption of a non-dimensional definition of the layout description. This non-dimensional approach means that the element descriptions held in the definition data files do not include information relating to the shape or geometry, this being determined as and when required. The absence of shape data in the boundary element descriptions also permits the hull form envelope to be modified without having to

redefine the internal components of the layout. This feature enables deformations of the design hull form to be carried out and even a completely different form to be considered, thus permitting the effect of hull form variations on the distribution of internal space to be determined.

5. COMPARTMENT DEFINITION

The process of compartment definition is considered as being distinct from that of layout definition. The definition of an internal arrangement will inevitably result in the creation of enclosed spaces, and it is the process of the identification of these enclosed spaces which is termed compartment definition. The calculated properties of the identified compartments determine whether the design vessel will meet the contractural requirements as stipulated in the owner's specification, as well as influencing the physical characteristics of the vessel, such as its trim, stability and strength. There is obviously the need to be able to identify compartments and determine their properties rapidly so that an assessment can be made of a defined configuration.

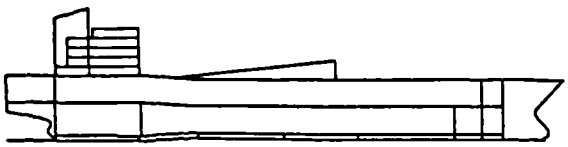

Fig.11 Boundary element intersections

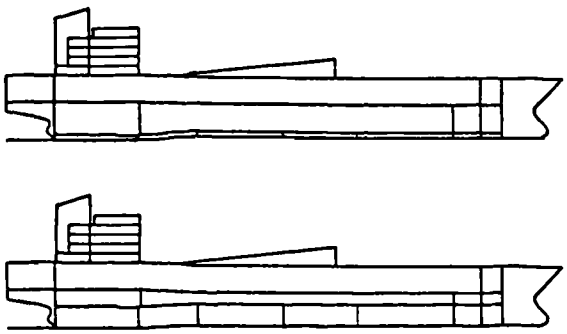

Fig.12 Effect of boundary relationships

Compartment definition is based on relationships between the internal layout boundary elements. The physical locations of these boundaries are, therefore, of no importance to the compartment definition, as they are only considered when the particulars of the identified enclosed compartments are to be determined. This enables the positions of the internal boundaries to be changed without the compartment definition having to be modified.

The development of this approach has resulted in a relational data handling technique which is considered original.

5.1. Relational Data Handling

As described earlier, the whole of the internal arrangement methodology is based on the description and manipulation of simple boundary elements which represent the major internal structure of the proposed vessel. The storage of the particulars of these boundaries together with information regarding the relationships between the various elements, presents considerable data handling problems even before the task of relating these boundaries to compartment definitions is considered.

When the data handling routines were being developed for inclusion in the system, a number of problems were identified, for which solutions had to be found, namely:

i) different boundary types requiring different description data,
ii) inherent physical relationships between boundaries,
iii) effect of model size on the complexity of the data handling problem

The relational data handling methodology developed for inclusion in the system is shown graphically in Fig.(13). It can be seen to comprise three major elements; the boundary definition file (index system), element files (boundary and geometry data), and the compartment definition file.

5.1.1 Boundary Definition File

This system element can be considered as the main indexing procedure for the layout definition routines described earlier. The file consists of three basic parameter groups which combine to form the layout index and boundary relationship indicator.

As an internal layout is defined by the system user via one of the methods provided, this index file is constantly updated to provide an accurate record of the design development. Each boundary element is assigned a unique numerical identifier which is used as the main reference point for all the boundary relationship evaluations and

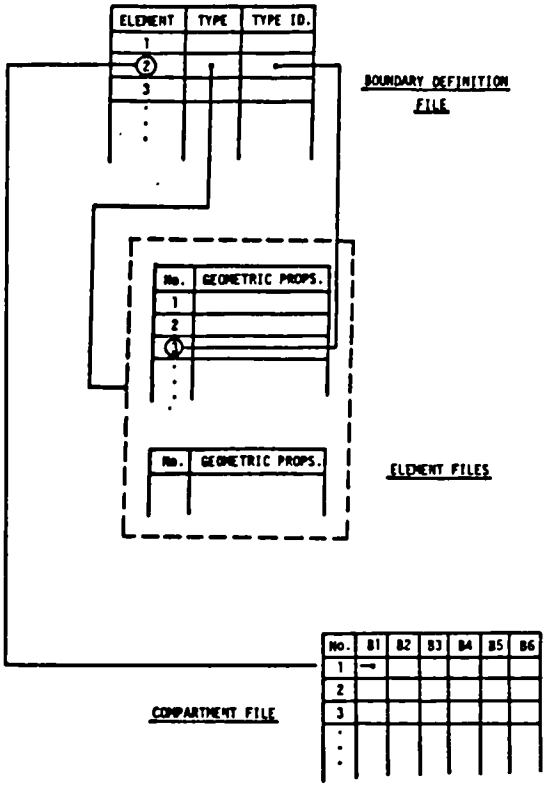

Fig.13 Relational Data Structure of Compartmentation Module

compartments definitions, as well as parameters which define its type, and its relative location within the relevant boundary type sub-set.

5.1.2. Element Files

Each boundary sub-set has an element file which is structured to accommodate the data required to give the necessary geometric definition of that particular element type. The particular boundaries in these sub-sets are assigned local identifiers which correspond to the particular identifier contained in the boundary definition file described above, thus enabling the particulars of any individual boundary element to be extracted simply by knowledge of its unique boundary element identifier.

5.1.3 Compartment Definition File

For each compartment defined, a record is entered in the compartment definition file which contains the identifiers of the group of boundaries which combine to represent the enclosure. As this method of defining a compartment does not directly involve details of its extent, location etc., then modifications can be made to the geometric definitions of the boundary elements without having any effect on the compartment definition particulars.

6. DETERMINATION OF COMPARTMENT PROPERTIES

In order that the quality of the proposed internal layout, and hence compartment arrangement, can be assessed, the geometric properties of the individual compartments must be calculated. This includes the determination of the volume, centroid location and free surface moments of each of the component compartments. These may be used by other program modules of the design system.

A given compartment is described in terms of a group of boundary elements, as mentioned previously, the positions of which determine its associated properties. To permit the calculation of the geometric properties the relevant boundary numbers contained in the compartment definition file are used to determine the types of boundary involved (by introducing the boundary definition file) and their locations within the type specific data set. The individual element files are then interrogated to provide the necessary geometric data to enable the properties of the compartment to be determined.

In common with all the other data definition routines interactive graphics are adopted for the compartment definition procedure. This approach means that the system user is able to rapidly define proposed compartment arrangements and make modifications without having to undertake extensive data input. Options are provided within the system for the definition of individual compartments by indicating a point within the relevant boundaries in both profile and sectional views of the defined layout. With knowledge of the location of this point within the compartment, the system is able to determine which of the defined boundary elements of the internal layout combine to form the compartment boundaries. The user is then invited to supply a compartment identifier and a compartment function label, so as to provide a means of database identification at a later stage. The user also defines the allowances used to covert the calculated moulded particulars to values which allow for associated internal structure and the practice of not filling compartments and tanks to full capacity.

No	COMPARTMENT	FUNCTION	AFT END	FWD END (m Fwd AP)	LCG	VCG (m AB)	VOLUME (cu.m)
1	DEEP TANK	WATER BALLAST	121.920	127.635	124.538	5.815	203.0
2	No.1 D.B. TANK	WATER BALLAST	121.920	127.635	125.520	0.889	21.0
3	No.2 D.B. PORT	WATER BALLAST	87.630	121.920	98.230	0.871	145.0
4	No.2 D.B. STBD.	WATER BALLAST	87.630	121.920	98.230	0.871	145.0
5	No.3 D.B. PORT	WATER BALLAST	67.310	87.630	75.769	0.844	138.0
7	No.3 D.B. STBD.	WATER BALLAST	67.310	87.630	75.769	0.844	138.0
16	A.HEELING (P)	WATER BALLAST	41.910	80.010	60.782	5.322	697.0
17	A.HEELING (S)	WATER BALLAST	41.910	80.010	60.782	5.322	697.0
						TOTAL	2184.0

No	COMPARTMENT	FUNCTION	AFT END	FWD END (m Fwd AP)	LCG	VCG (m AB)	VOLUME (cu.m)
6	No.3 D.B. CENTRE	HEAVY OIL	67.310	87.630	77.470	0.750	253.0
						TOTAL	253.0

Fig.14 Compartment particulars

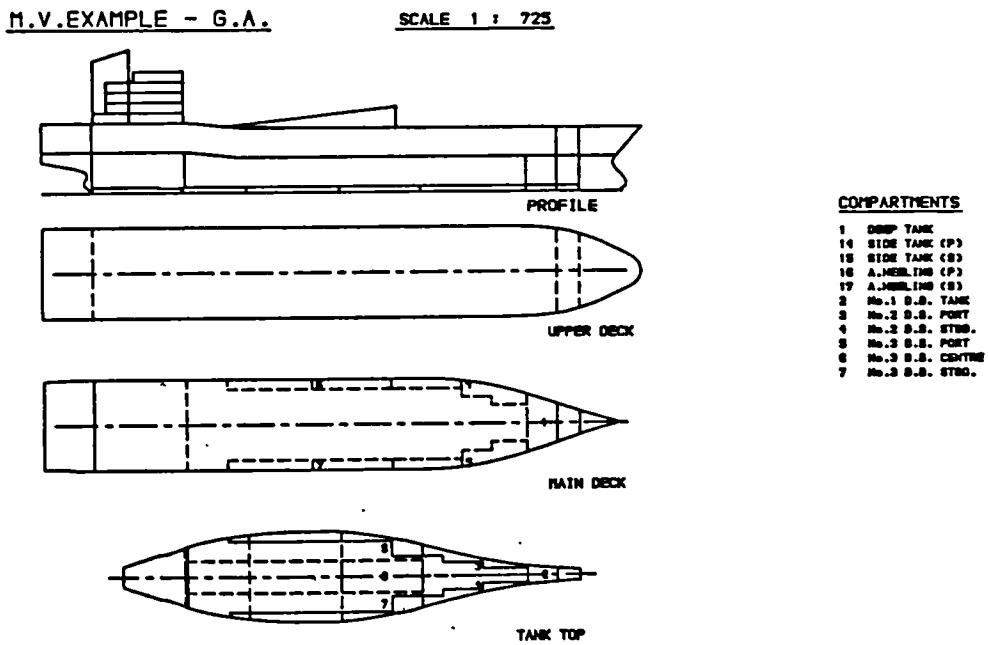

Fig.15 General arrangement of design vessel

In addition to producing textual outputs of the calculated compartment particulars as shown in Fig.(14), the system provides the user with a graphical representation of the arrangement of the compartments on profile and deck views of the vessel as illustrated in Fig.(15). For each of the defined compartments the system automatically produces information for a sounding diagram, which relates compartment volume and vertical centre of gravity to height above the compartment base. Not only does this information provide the designer with the means of assessing the arrangement and making alterations to it in order to meet the space requirements, but it also establishes the data required for the investigation of various loading arrangements in terms of trim and stability and longitudinal strength characteristics.

The flexibility of the layout definition and compartmentation procedures enables the designer to carry out assessments of several arrangements in a very short time and with the minimum of effort.

7. ANALYSIS OF DESIGN PROPOSALS

7.1 Trim and Stability Assessment

For a design proposal to be acceptable, it must be shown to exhibit favourable trim and stability properties for a selection of loading arrangements representative of the conditions under which the vessel is likely to be operated. In order that the designer can carry out such investigations, the design system incorporates elements which provide for the definition of various loading arrangements based on the compartment information previously produced by the system.

The information derived from the compartment definition by the system can be expanded in order that most items not explicitly assoicated with the definition can be taken into account. Such items may include smaller tanks in the engine room, or items of cargo carried on the upper deck.

Particulars concerning the distribution of the vessel lightmass must be supplied by the user or obtained from the mass estimation modules of the design system. This provides an overall mass distribution for use in the loading condition investigations.

The trim and intact stability elements of the design system provide a means of assessing the quality of a design proposal at a very early stage in its development. This allows the detection of an unacceptable proposal before the design has progressed very far. The composite nature of the investigations will undoubtably provide the user with considerably more information than would normally be obtained at the concept stage of the design process.

7.2. Longitudinal Strength Investigation

A procedure has been developed and incorporated into the preliminary design system which will evaluate the longitudinal distribution of vertical bending moments and shearing forces for any specified loading arrangement. For the given loading condition the weight forces are determined by the superposition of the defined loading condition onto the distribution of the lightship mass, which is itself made up of concentrated and distributed items with the remainder mass being assumed to possess a parabolic distribution. The curve of buoyancy for the given loading arrangement is determined from the hull form description such that the total buoyancy force and its point of application are equal to the overall mass and its associated centroid. The distribution of the resultant forces is integrated to provide values of vertical shearing forces along the length of the vessel with further longitudinal integration giving the distribution of vertical bending moments along the vessels length. The result obtained from the system for a given loading condition can be obtained in both textual and graphical form. This information enables the designer to make an assessment of the suitability of a proposed loading arrangment and to implement changes if necessary.

8. FUTURE DEVELOPMENTS

8.1 Application of Expert Systems to Ship Design

The modules of the design system which have been described here provide the designer with the means of defining and developing the hull form and internal arrangement of a design proposal. Although the various elements of the modules will rapidly evaluate a given proposal all the decisions regarding the development of the design are made by the designer and based on his personal experience and knowledge. This reliance on user expertise not only causes delays in the design process but also means that the quality of the final design proposal is totally dependent on the ability of the user. An alternative to the need for a system user with a high level of technical knowledge would be the incorporation of a so-called 'Expert System'.

An expert system is defined as a computer system capable of representing and reasoning about some knowledge-rich domain with a view to solving problems and giving advice. The

requirements of any expert system are that:

- it can deal with matters of a fairly complex nature which normally require a high degree of human expertise,
- it must exhibit high performance in terms of speed and reliability,
- it must be able to justify any decisions made and demonstrate any path of reasoning.

Expert systems are being developed to incorporate the heuristic knowledge of experienced ship designers together with the rules and regulations of the various regulatory bodies concerned with ship design. These expert systems will also advise the user on matters concerning shipyard standards, e.g. the utilization of standard accommodation modules.

Expert systems within the design system described here will advise the user during the development of a design proposal which incorporates the best of current practice and complies with all the relevant statutory requirements.

9. CONCLUSION

This paper has described the methods used in the development of two of the main modules of the Integrated Ship Design System being developed at the University of Newcastle-upon-Tyne on behalf of British Shipbuilders Ltd. The intention is to provide the practising ship designer with a new computer based tool for use at the preliminary stage of the ship design process.

This tool not only allows the designer to develop a design proposal in a much reduced time scale, but also ensures that the decisions made regarding the development of the design have a firm engineering basis and are not simply the result of experience or intuition. The system meets this specification and in most cases its use can be extended far beyond the concept or preliminary design stages.

Even in their stand alone form the individual modules of the design system mark a significant advance in the use of computer based methods in early design studies. In its final form, when all of the individual modules have been completed and assembled, the system will be one of the most comprehensive preliminary ship design packages available.

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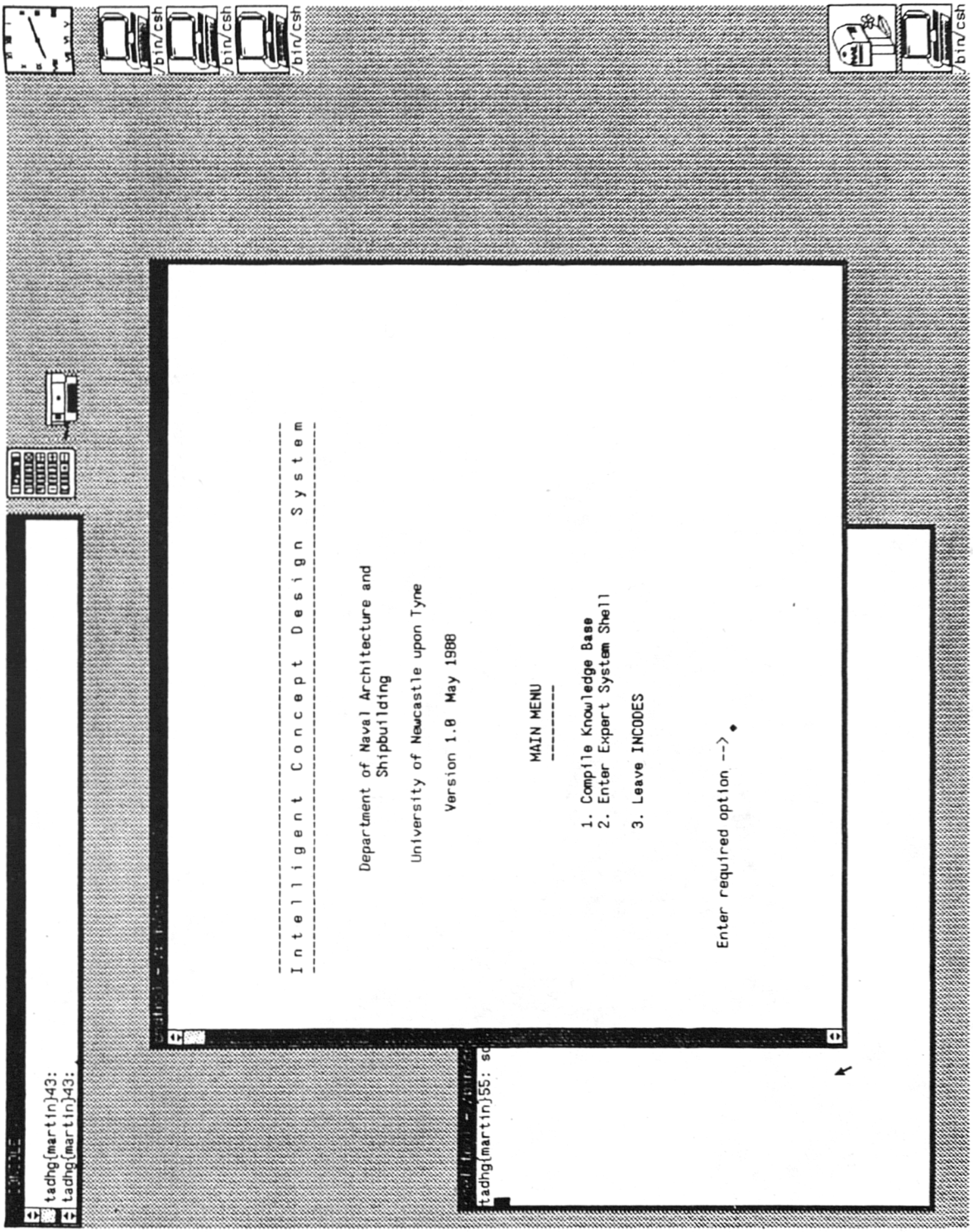
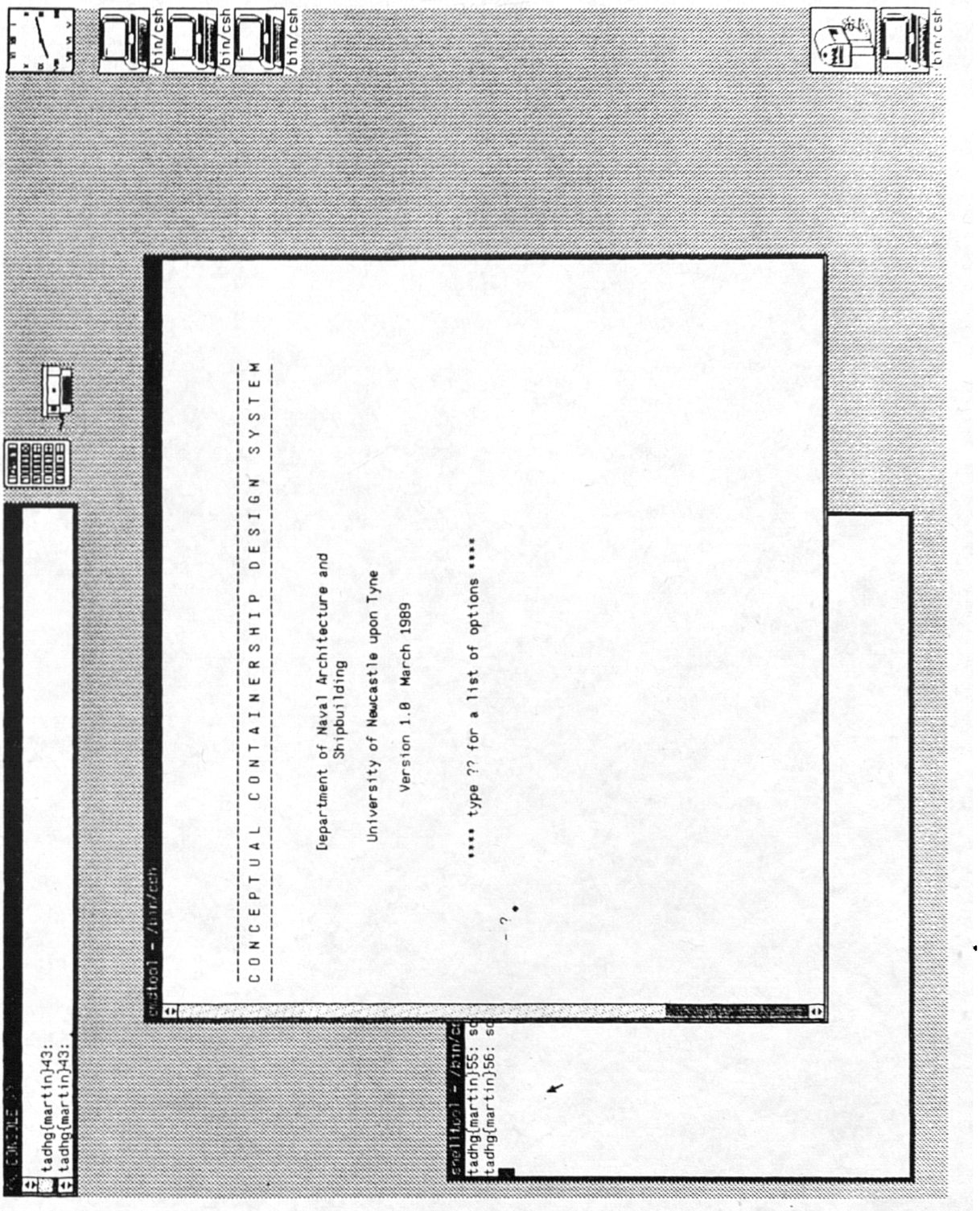
APPENDIX II

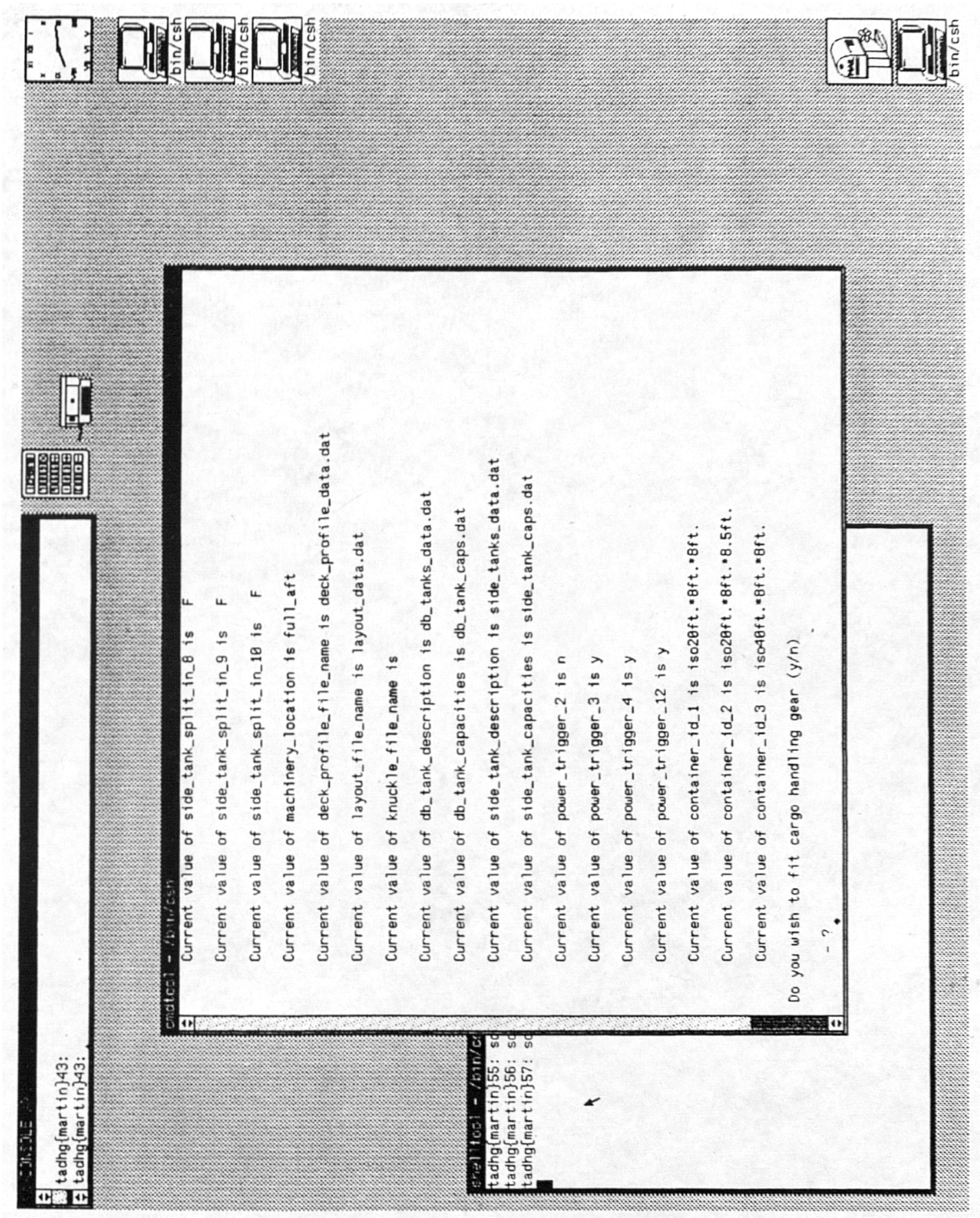
Examples of User/System Dialogue.



The menu displayed upon entering the INCODES environment on the SUN workstation.



The display after invoking the containership design knowledge base.



Informing the user as to the default values of some of the parameters contained in the knowledge base, and prompting for user input.

```
tadhg(martin)43:
tadhg(martin)43:

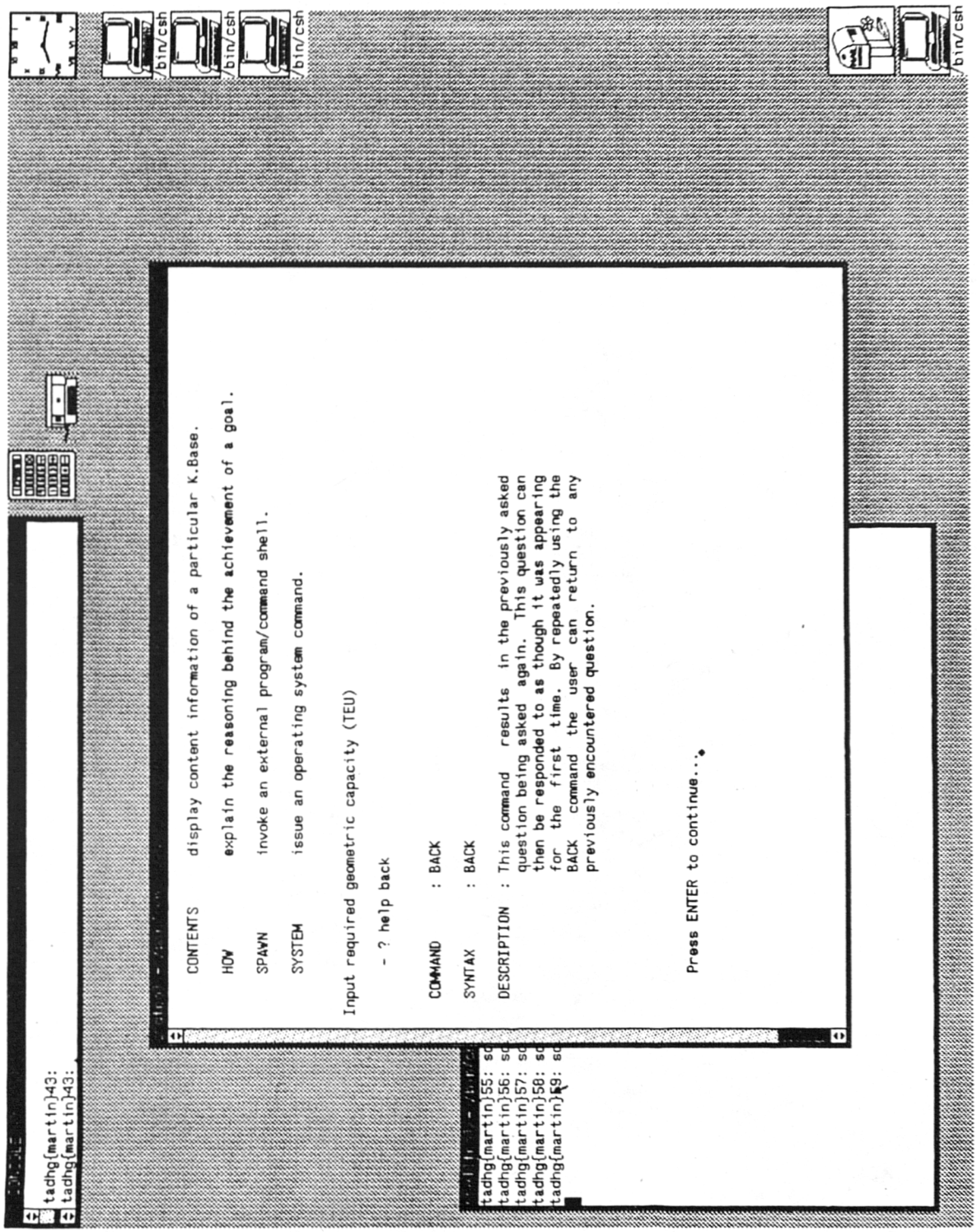
Input required geometric capacity (TEU)
  - ? ??

                Expert System Shell User Options
                ---------------------------------
                          ( Level 2 )

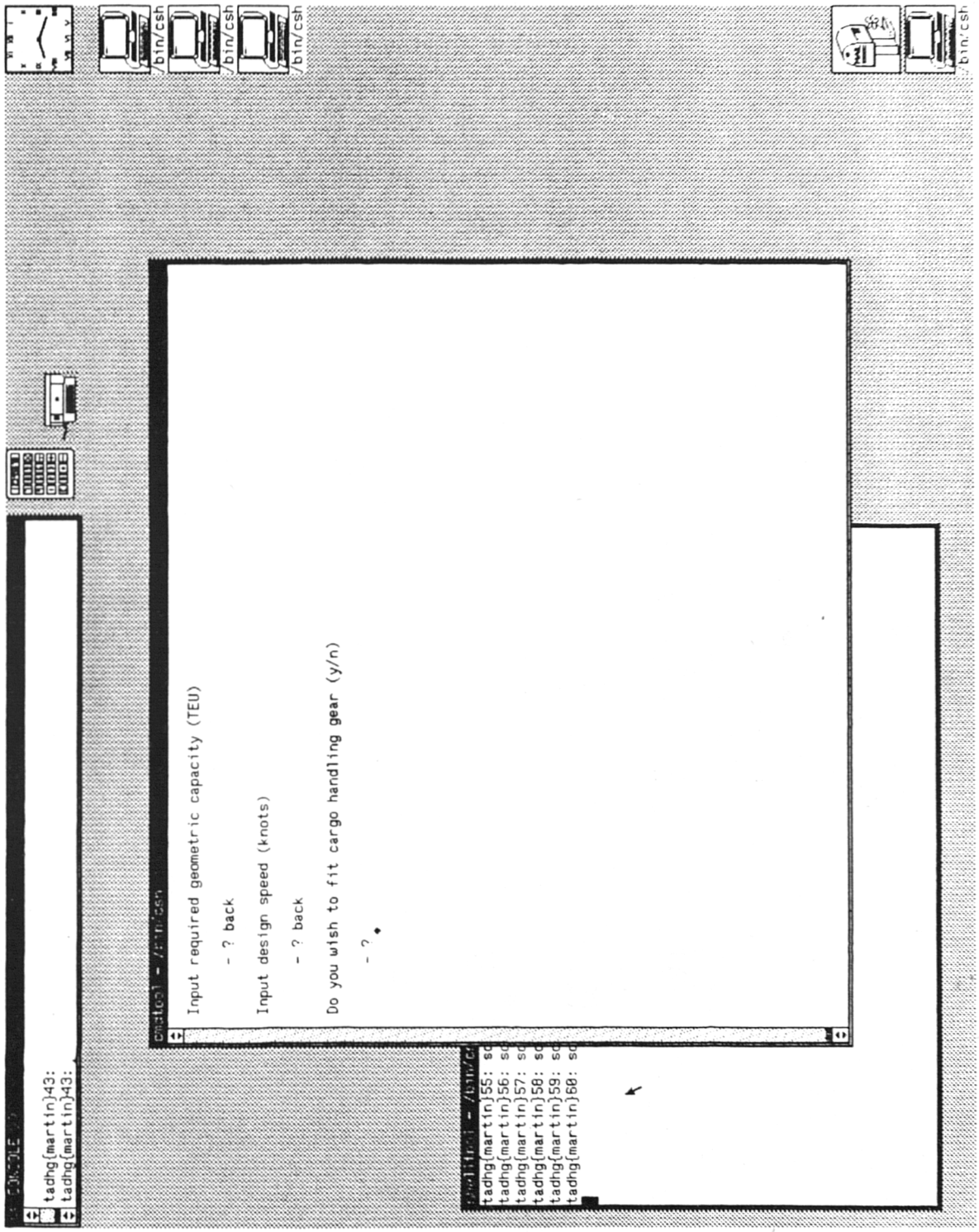
??          display this message.
HELP [option] display more information about the specified option.
BASES       display the currently available Knowledge Base.
LOAD        load the specified knowledge base into the shell.
GO          start the consultation.
STOP        stop the current consultation.
RETRIEVE    retrieve a previous consulation session.
STORE       store the current values of all parameters.
CHANGE      change the value of an individual parameter.
STATUS      display the status of the current session.
WHERE       where is an individual parameter assigned.
VALUE       display the value of a particular parameter.
BACK        go back to previous question.
DATAFILES   what datafiles are available for display.

tadhg(martin)55: sd
tadhg(martin)56: sd
tadhg(martin)57: sd
tadhg(martin)58: sd
```

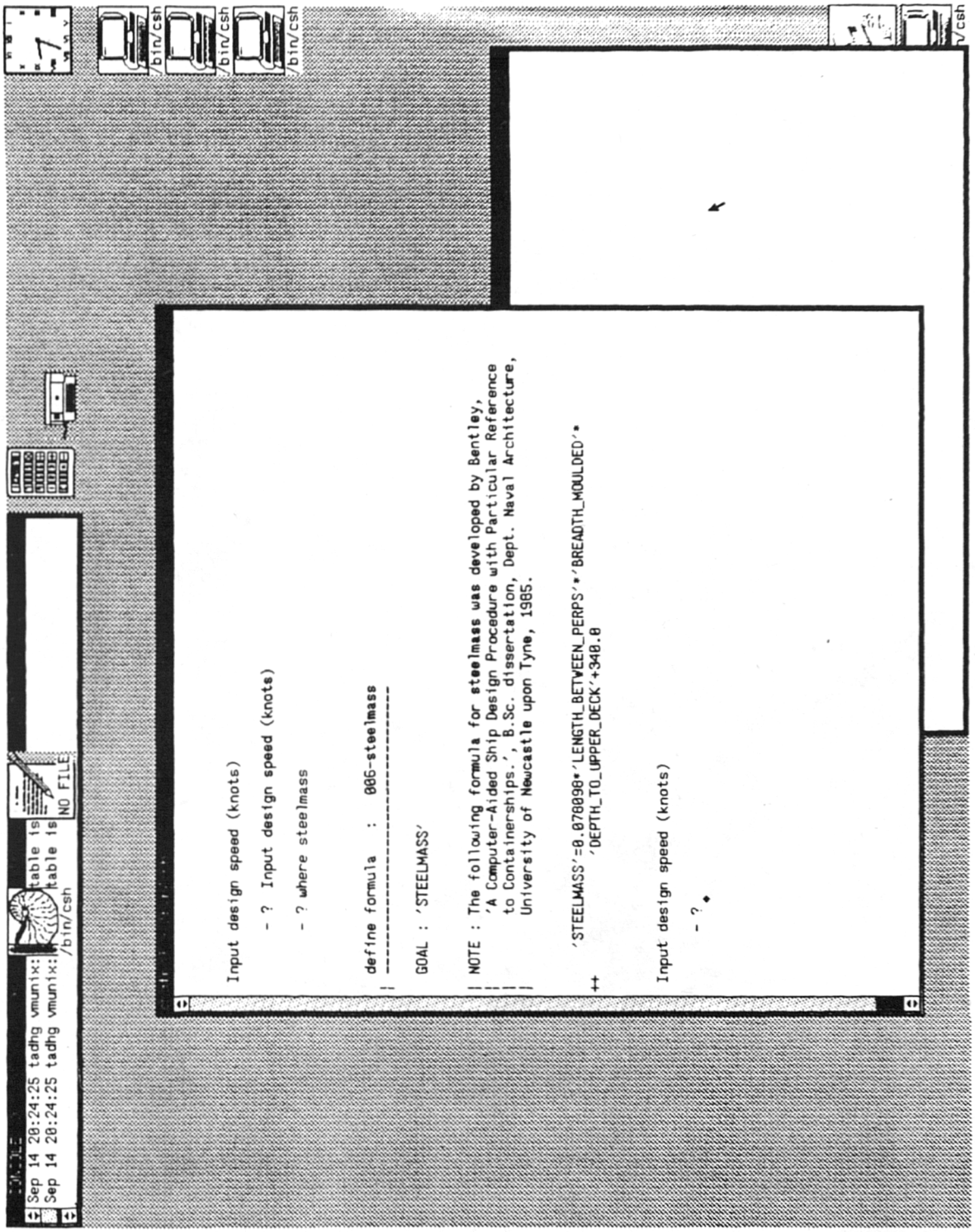
The result of asking the shell to display the available user options.



Invoking the on-line documentation facility.



Back-tracking to previously encountered questions.



Examining the contents of the knowledge base.