1. Gedurende het conceptueel ontwerpproces hoeft geen indeling van een ruimte gemaakt te worden, mits de drie ruimtebalansen: volume, oppervlakte en lengte beschouwd worden.

2. Een concept exploratiemodel kan alleen flexibel genoemd worden als de ontwerpvraagstelling omkeerbaar is.

3. Door ontwerpkennis van de toepassing te scheiden wordt het mogelijk alternatieve ontwerppoplossingen te exploreren zonder de aanwezige kennis opnieuw te implementeren.

4. Een ontwerper hoort alleen vertrouwen te hebben in een antwoord van een ontwerpmmodel indien de algoritmen in het model aan hem bekend zijn (geworden).

5. Een ontwerpgereedschap gebaseerd op kennistechnologie ondersteunt de grootste passie van een ontwerper: zijn verzamelwoede.

6. Een computerondersteund gereedschap moet zich herhaalbaar gedragen, een ontwerper niet.

7. Een ontwerpprobleem wordt pas een ontwerpuitdaging indien de juiste gereedschappen gebruikt kunnen worden.


9. Een oorlog is nooit zonder doel, doelloos zijn slechts haar gevolgen.

10. Het recht op deeltijdarbeid is een voorrecht.

11. Kennis wordt weten zodra men weet wat kennis is.

12. De definitie van seks is afhankelijk van de plaats waar en de toestand waarin men zich bevindt.

13. Het wissen van fotografisch materiaal draagt in belangrijke mate bij aan het wissen van het collectieve geheugen.

14. Door op juiste wijze minimale kracht uit te oefenen kan men zich met één paardekracht voortbewegen.

A knowledge-based Concept Exploration Model for Submarine Design
A knowledge-based Concept Exploration Model for Submarine Design

PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus Prof. ir K.F. Wakker
in het openbaar te verdedigen ten overstaan van een commissie,
door het College voor Promoties aangewezen,

op dinsdag 2 maart 1999 te 16:00 uur

door

Clemens Gerardus Johannes Maria van der NAT

scheepsbouwkundig ingenieur
geboren te Sassenheim
Dit proefschrift is goedgekeurd door de promotoren:

Prof. ir J. Klein Woud
Prof. ir D. Stapersma

Samenstelling promotiecommissie:

Rector Magnificus, voorzitter
Prof. ir J. Klein Woud Technische Universiteit Delft, promotor
Prof. ir D. Stapersma Koninklijk Instituut voor de Marine, promotor
Prof. W.J. van Griethuysen " University College London
" BSc, MSc, PhD, C Eng, FRINA, RCNC
Prof. dr ir M.J.W. Schouten Technische Universiteit Eindhoven
Prof. dr H. Koppelaar Technische Universiteit Delft
Prof. ir A. Aalbers Technische Universiteit Delft
dr ir C.A. Prins Rotterdamsche Droogdok Maatschappij Submarines

Published and distributed by:
Delft University Press
P.O. Box 98
2600 MG Delft
The Netherlands
Telephone: +31 15 2783254
Fax: +31 15 2781661
E-mail: DUP@DUP.TUDelft.NL

ISBN 90-407-1829-6

Copyright © 1999 by C.G.J.M. van der Nat

All rights reserved. No part of the material protected by this copyright notice may be reproduced or utilised in any form or by any means, electronic or mechanical, including photocopying, recording or by any information storage and retrieval system, without permission from the publisher: Delft University Press.

Printed in the Netherlands
Aan Yvanka en Vivian
"10,000 miles under the sea", how to do?
# CONTENTS

<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>vii</th>
</tr>
</thead>
<tbody>
<tr>
<td>PREFACE</td>
<td>xi</td>
</tr>
</tbody>
</table>

## 1

**INTRODUCTION**  
1.1 Background ........................................................................ 1  
1.2 Objective ........................................................................... 5  
1.3 Main philosophy .................................................................... 6  
1.4 Organization of dissertation .............................................. 6

## 2

**LITERATURE REVIEW ON SHIP DESIGN PROCESS**  
2.1 The Design process .................................................................. 9  
2.1.1 Design strategies ................................................................ 10  
2.1.2 Design tasks ...................................................................... 13  
2.2 The Concept Exploration Model .............................................. 15  
2.2.1 Existing Concept Exploration Models .................................. 15  
2.2.2 SUBmarine Concept Exploration Model ................................. 17  
2.3 Conclusions .......................................................................... 19

## 3

**OVERVIEW OF SUBMARINE DESIGN KNOWLEDGE**  
3.1 Submarine design process ..................................................... 21  
3.2 Submarine sizing .................................................................... 23  
3.2.1 Carrying platform ............................................................ 23  
3.2.2 Manoeuvring ..................................................................... 25  
3.2.3 Energy supply .................................................................... 29  
3.2.4 Ship management .............................................................. 30  
3.2.5 Navigation and observation .............................................. 30  
3.2.6 Communication .................................................................. 31  
3.2.7 Life support ....................................................................... 31  
3.2.8 Special functions ............................................................. 31  
3.3 Submarine balancing ............................................................. 32
3.3.1 Space/weight balance ........................................ 32
3.3.2 Energy balance .............................................. 33
3.3.3 Manning balance ........................................... 33
3.3.4 Cost balance .................................................. 34
3.4 Submarine performance calculations ........................................ 34
3.4.1 Carrying platform .......................................... 34
3.4.2 Manoeuvring ............................................... 35
3.4.3 Energy supply ............................................. 39
3.4.4 Ship management ......................................... 39
3.4.5 Navigation and observation .................................. 39
3.4.6 Communication ........................................... 39
3.4.7 Life support .............................................. 40
3.4.8 Special functions ......................................... 40
3.5 Conclusions ..................................................... 40

4

PROBLEM INTERPRETATION ............................................. 41
4.1 Submarine problem interpretation .................................. 41
4.2 The top-level problem .......................................... 42
4.3 Submarine sizing problem ...................................... 43
  4.3.1 Demarcation of components .................................. 43
  4.3.2 Determination of budgets ................................... 44
4.4 Submarine balancing problems .................................... 47
  4.4.1 Space balancing .......................................... 47
  4.4.2 Weight balancing ......................................... 47
  4.4.3 Energy balancing ......................................... 47
4.5 Performance prediction problems .................................. 48
  4.5.1 Calculation of performance characteristics .................. 48
  4.5.2 Comparing achieved performance to mission specifications ....... 48
4.6 Implications for this research .................................... 48

5

KNOWLEDGE ACQUISITION METHODS .................................. 51
5.1 Submarine knowledge acquisition methods ......................... 51
  5.1.1 Data collection .......................................... 52
  5.1.2 Analysing data ........................................... 53
  5.1.3 Coding the design knowledge ................................ 54
5.2 Conclusions ..................................................... 58

6

THE SUBMARINE DESIGN MODEL .................................. 59
6.1 Submarine design models ....................................... 59
6.2 Models for sizing .............................................. 62
  6.2.1 Models for object sizing ............................... 62
  6.2.2 Models for inboard space and weight sizing .... 69
  6.2.3 Models for inboard structure sizing ............... 77
  6.2.4 Models for outboard space sizing ................. 79
  6.2.5 Models for outboard structure sizing .......... 85
6.3 Models for balancing ........................................ 85
6.4 Models for performance prediction ..................... 86
  6.4.1 Carrying platform .................................... 86
  6.4.2 Manoeuvring ......................................... 87
  6.4.3 Energy supply ....................................... 91
  6.4.4 Life support ......................................... 94
6.5 Conclusions ................................................ 94

IMPLEMENTATION ................................................. 97
7.1 Tool features for candidate design tools .............. 97
  7.1.1 Tool features for numerical knowledge ........... 98
  7.1.2 Tool features for geometric knowledge .......... 103
  7.1.3 Tool features for topological knowledge ........ 105
7.2 Identifying candidate tools ................................ 105
  7.2.1 Knowledge-based tools ................................ 105
  7.2.2 Procedure-based tools ............................... 120
7.3 Quality control of the prototype ......................... 123
7.4 Conclusions ................................................ 123

USABILITY OF CONCEPT EXPLORATION MODEL .................. 125
8.1 Concept design case ...................................... 126
  8.1.1 Concept identification ............................. 128
  8.1.2 Define and size inboard objects ................... 128
  8.1.3 Define and size inboard concept .................. 131
  8.1.4 Define and size the primary and inboard secondary structure .................. 133
  8.1.5 Define and size outboard objects .................. 134
  8.1.6 Define and size outboard concept ................. 135
  8.1.7 Define and size secondary outboard structure .... 136
  8.1.8 Determination of propulsion performance ........... 136
  8.1.9 Define and size supplementary objects .......... 138
  8.1.10 Determine weight balance .......................... 138
  8.1.11 Determine hydrostatic performance ............... 139
  8.1.12 Determine energy-autonomy ....................... 141
8.2 Concept variation cases ................................ 142
  8.2.1 Propulsion object (main electric motor) variation 143
PREFACE

"May 7 2001. John, your submarine design office is studying ten different options for layout and component choices as described in the working paper. The client has come-up with six new ideas, which have to be analysed. We would like you to analyse the impact of these ideas on the overall design. As a consequence we increase your budget from 5 to 8 days in order to complete the full analysis.

Yours, Peter."

This could be a part of a typical request for an additional study assignment. The ship designer has to analyse a total of sixteen different options for lay-out and component choices for a new submarine in only an eight day period. Using current design methods it is unthinkable to demand such a performance from anyone, as each option requires extensive calculations partly by hand, specific software or by general software like (re-) programmed spreadsheets.

As at present the analysis of each design option involves great costs and the number of analysed variants is limited. In practice those assumed most promising are selected for analysis, which in most cases are the variants that come closest to the situation found in already existing, known designs. This way of working does not stimulate the exploration of new concepts, as analysis costs would become too high.

To allow analysis as flexible and as fast as described in the above request, a design tool has to be developed. The systematic methods followed leading to such a tool are the main topics of this thesis. One of the features of this tool is the facility to organise information systematically from an already existing body of knowledge. As the body of knowledge can be large and complex, it is necessary to manage the quality of the knowledge in a systematic and formal way throughout the development process of the tool. One of the keys used in the quality control is that the representation of information is compatible with representations used by designers.

The project was launched in 1992; the first stage was completed in 1993 with a description of a first prototype. During the three following years, the description was continuously extended, implemented and validated. The prototype is called 'SUBCEM', the first three letters refer to the SUBmarine, which is used as application and the last three letters refer to the name of the design model, a Concept Exploration Model. Although SUBCEM shows the feasibility of a submarine design tool for the conceptual design stage, the investigation of the applied methods goes beyond the implementation of this prototype.
1

INTRODUCTION

What do we know, when we do know?
Plato

This chapter introduces the background and objectives of the dissertation described in this thesis. The dissertation presents an approach to the development of a knowledge based tool for conceptual submarine design. First, the main philosophy behind the development is introduced, followed by an overview of the structure of the thesis.

1.1 Background

This thesis discusses the application of knowledge based techniques in the conceptual design process of submarines. Before the problem area of this thesis is presented, first some background information is provided about current ship design practise and the applied techniques.

What is the purpose of ship design? Ship design is the process of constructing a design description of a realisable ship, at a level of detail required for production and assembling, that satisfies a desired behaviour in specified operational conditions. The design description, or also called concept, contains information about the size, layout and performance of the ship and about the components by which this performance is achieved. The performance specification is a method to quantify to what degree the specified functions must be satisfied. What performance is relevant depends on the functions that the ship has to fulfill. Typically the components required for fulfilling certain functions influence the performance of components required for other functions. This multi functional nature of design prevents applying a straightforward design procedure for producing a design description at a level of detail required for production and assembling. To achieve a solution, an iterative design procedure is applied, which
is popularly shown by a ‘spiral’ [Nordin, 1990]. The middle point of this spiral illustrates the solution found and each circular sector illustrates a function in the design description. Each turn of the spiral represents a stage in the life cycle of the design process.

Figure 1.1 shows the ship life-cycle stages as used in current (naval-) ship building. The design process contains the first five stages of the life cycle of a boat. In the first stage (pre-feasibility study), the operational requirements are defined by the client. In the second stage (feasibility study) conceptual design studies are performed ending with feasible concept specifications. The following stages deliver design information with an increasing level of detail until the agreed contract specifications are derived [Holtackers, 1991]. Thus, at each stage of the design process, requirements and performance values of the ship are specified at a level of detail that can be interpreted for a defined purpose in a next design stage. Regardless of the level of detail, the performance must be valid, thus a performance at the conceptual level must also be reached at more detailed levels. A typical example in ship design is the maximum speed performance, which is limited by the installed propulsion power. As the design process progresses changes in the design description occur which might affect the size, layout and shape of the boat. If the performance does not meet the defined criterion in a later stage of the design, then either the imposed performance has to be relaxed, or the propulsion plant has to be re-designed, or the resistance of the boat must decrease by re-sizing and/or re-shaping the boat. These actions are not desirable, especially when they effect the total ship design, because they either decrease the quality of the design outcome or increase the time required to produce a satisfying outcome. For this reason the decisions made in the early stage of the design have far-reaching effects on the outcome of the design process [Mistree, 1991].

Figure 1.1  Life-cycle of ship including its design information
Which types of information are relevant in the design process? To describe the performance of a ship and its components, three different types of information are distinguished: numerical, geometric and topological information. Numerical information contains a mathematical description of the ship characteristics. This description includes parameter values, and the relations between the parameters expressed by equations and constraints. Examples of models using only numerical design descriptions are presented in: [Huggins, 1994] for underwater vehicles used in oceanographic research, [Jackson, 1983] for military submarines, and [Allmendinger, 1990] [MacGregor, 1990] for general underwater vehicles. Geometric descriptions contain the form and size of the space characteristics. An example of a model using only geometric knowledge is presented in [Hyde, 1992]. This model sizes the deck area and volume within a given hull and superstructure of a ship. Topological descriptions contain the lay-out of the ship. Examples of models using both geometric and topological knowledge are presented by Andrews [1985], Brown [1987] and Carlson [1987]. These models support the definition of a surface-ship’s general arrangement by defining and sizing on one hand the available internal space subdivided by decks and bulkheads, and on the other hand the required spaces to fulfill defined functional requirements.

How can design tools support the designer while producing a design description with all types of (relevant) information? From the mid-1970s a growing emphasis is given to improving the capabilities of design tools which can help the designer to produce ‘improved’ early stage design descriptions. The developed tools are capable to investigate and compare large amount of different designs [Eames, 1976][Nethercote, 1981][Schild, 1992][Georgescu, 1992]. Basically, these tools have automated the first (iterative) cycles of the design spiral using a fixed sequential design process and uniform specifications. The algorithms often only include (crude) numerical relations and geometrical and topological aspects are assessed numerically using a pre-defined layout. In spite of the references, only a few scientific studies have reported practical experiences with these tools. Various shortcomings have been addressed by designers in practice, such as: insufficient insight in the applied knowledge, ignoring some relevant design aspects, and inability to influence the quality of answers. More recently, knowledge-based tools were introduced to overcome these shortcomings and to support the development of new design tools [Welsh, 1990][MacCallum, 1987]. The first generation of these knowledge-based tools employed one relatively simple inference engine working on a knowledge base in a particular format, usually production rules. The Inference engine contains a reasoning mechanism to draw conclusions about a problem, by matching problem facts that are discovered during the solving process with design knowledge in the knowledge base. Research at the University of Newcastle [Welsh, 1990] showed an application of such a tool, used for representing container ship design descriptions. More advanced generations of knowledge-based tools employ also other knowledge representations like frames and semantic networks [MacCallum, 1987]. During the development of these tools the acquisition of relevant knowledge from practising designers and representing this knowledge into a knowledge-base is shown as the most crucial activity. The quality of knowledge acquisition is largely dependent on the level of accuracy of the knowledge. Methods for systematic ship design knowledge
acquisition are generally only concerned with numerical knowledge, and neglect topological and geometric knowledge. This neglect does not imply that overall shape and internal arrangement are not considered, as topological and geometrical knowledge can be translated into numerical shape and arrangement parameters. However, this translation introduces an extreme amount of numerical knowledge, which must be redefined for each alternative design description. One of the first research programs integrating a limited amount of topological and geometric knowledge into the initial ship sizing process is described by Andrews [1985] and Carlson [1987]. In these references topological knowledge is defined by a sequence of spaces in the ship, and geometrical knowledge is defined by volumes and areas. Note that lengths in these reference are not part of the geometrical knowledge. Other research programs focus in particular on length as the most important geometric knowledge for sizing the ship [Brown, 1987].

Apart from the conceptual design tools there are also several tools already available for the more detailed design stages, for example the preliminary design tool CASE [Laansma, 1992] or SUBCON [Andrews, 1996], both are applied in submarine design. Typical for these tools is the application of 3-dimensional modelling and visualisation techniques, which are used to locate so-called 'building blocks' in the space of the submarine. A 'building block' is a geometric description of one or more components which have a particular capability. This geometric description may be a 3-D surface (such as a deck or pressure hull) or a 3-D solid (such as an equipment or even a compartment). A process of 'graceful refinement' is proposed [Andrews, 1996], starting with high level building blocks such as main machinery spaces or accommodation spaces and ending with discrete components such as anchor and propulsion motor. The 3-D geometric description and location in the 3-D spaces is especially valuable for the refined stages of design. However, to enable a more accurate prediction of the size of the submarine, the geometric description must contain details about shape and dimensions of the components. This information can, for example, be found in component databases of previous designs. A more accurate source of information are the component suppliers, which become involved during the preliminary stage of the design. Usually the preliminary design tools do not include component sizing algorithms, which can predict the geometric description as accurate as the above mentioned sources. Lacking sizing algorithms becomes especially a disadvantage when characteristics of different components depend on each other, such as a propulsor, main electric motor and the main battery system, which are in reality often delivered by different component suppliers. Although one can live with the lack of sizing algorithms in a preliminary design stage the interdependency between components and thus "free" sizing is essential during conceptual design.

Besides the geometric description each block also includes detailed weight properties (such as mass, displacement and their centroids), energy properties (such as power demand and heatload) and manning properties. These properties enable a check on the balance of weight, power and manning. Finally, after balancing the design, the performance characteristics can be determined.
1.2 Objective

From the background information provided in the previous paragraph is learned that in the initial stage of ship design a design description is generated.

The objective of this thesis is to find the major development issues which have to be considered during the development of a conceptual design tool which supports a designer while generating a design description of a complex technical product, such as a ship or submarine. The tool must assist the designer in performing sizing and trade-off studies in an efficient and flexible way.

‘Efficient’ means that the effort of a designer to solve a problem is reduced, enabling shorter development time and/or better quality. ‘Flexible’ means that new knowledge can be integrated easily, that a wide variety of design problems can be answered and that the design of the boat remains adjustable.

The development includes the process from acquiring knowledge to mapping this knowledge onto a program level. There are many steps in this process: identifying the problem, learning about the design-knowledge, its structure, selecting knowledge sources and extracting the knowledge from them, selecting the most promising supporting tools, encoding the knowledge in the tool, as well as verifying and validating the encoded knowledge. This thesis provides an in-depth look at the development process leading to the conceptual design tool. During knowledge acquisition it discusses the most commonly used techniques, like knowledge identification and modelling and provides guidelines for effectively conducting each of these techniques. Typical questions in this perspective are: what level of abstraction is defined for a representation, what body of knowledge in terms of algorithms is required and which aspects are relevant for the functioning of the boat. During implementation the thesis discusses the collection of tools, which are used for implementing the design knowledge and the underlying design approach. In order to select these tools, first some questions about essential features for each part of the tool are answered.

Although the term ‘complex technical product design’ has been used, the application of this thesis is focussed on the conceptual design of submarines with submerged displacement between 1000 - 3000 [ton]. Nevertheless, it is expected that the conclusions based on the thesis have broader application, because the thesis concentrates more on the process than on the application.

The term ‘conceptual design’ within the objective of this thesis demarcates the feasibility stage in the design process, starting with the functional specifications defined by the client and ending with a feasible conceptual design description. More detailed design than conceptual design is not considered, since for this task several tools are already available.
1.3 Main philosophy

The research area described in this thesis concerns the development of a software package producing conceptual designs. When developing a design tool, it is important to remember the overall aim of these tools, which is to improve the effectiveness of the organization using them. Improved organizational effectiveness can occur in many ways, such as improving the product quality, reduction of design costs, providing expertise within the organization where this capability is lacking and/or improving the reputation as a leader and innovator in the market. The motivation to improve the effectiveness is more solution driven, or in other words motivated by potential for future projects, than problem driven, which requires well-defined problems. As most design problems are not well-defined, the main philosophy used throughout the thesis follows Berkhout's statement:

"Concepts (is in this context meant to be 'design knowledge') are produced by experts. Sets of data are used in transforming concepts into designs (is in this context meant to be 'design descriptions'). Data are produced in previous designs and in real life. Which data are needed at what stage has to be decided by the designer. Design tools have to offer a facility of easy survey and selecting and evaluation of supposedly relevant data" [Berkhout, 1987].

The construction of a design can thus be viewed as a search of relevant data. Data is produced by examining design knowledge, which contain engineering methods based on empirical and/or physical algorithms. During the design process, it is the designer who selects relevant design knowledge depending on the results from produced or already available data. The design tool is not making the selections, but supporting the selection process.

The development of a tool based on the above given philosophy, is evaluated by assessing a prototype software package. This prototype is made to a level of detail and proportion needed to demonstrate the proof of the usability of the method. This suggests that the evaluation of the philosophy depends principally on the performance of the implementation. This observation is valid for the evaluation of any application of computer science to a particular problem, however the evaluation of the described philosophy goes beyond the application, as it can also be applied to other design problems.

1.4 Organization of dissertation

People interested in this thesis typically includes developers of ship-design tools, managers of such development efforts, and personnel tasked with implementing and using these technologies. The purpose of the following chapters is to show readers the methods required to acquire design knowledge and how to incorporate the derived design tool into the design process. Systematic knowledge acquisition is only successful
when both the design description and the way to derive the design description are fully understood. The structure of this thesis is developed in such a way that it will logically support this observation.

Chapter 2 introduces models for describing the design process. Such a model is intended to capture the strategy behind the sequence of states a design goes through, from initial specifications to final design description and the tasks that move it from state to state. Following on this inventory of design models, the important characteristics of the model used for conceptual submarine design are formulated.

Chapter 3 presents an overview of the submarine design focusing on the particular problems of designing a submarine, such as the balancing problem. The balancing problem is the crux of the submarine design problem and involves balancing five characteristics: space, weight, energy, manning and costs. The thesis does not give a detailed description of the submarine design models, as good references already exist on this subject e.g. [Arentzen, 1960][Allmendinger, 1990][Jackson, 1992][Buercher, 1994]. The purpose of this chapter is to present the submarine's functions for which components should be designed. An introductory text is given on different aspects of typical current components that are applied to fulfill the functions.

Chapter 4 discusses issues arising in representing submarine design knowledge. This chapter interprets the potential design problems, such as sizing, balancing and performance calculation problems. These problems contain numerical, geometrical and topological questions about the submarine. To reduce the number of questions, components are assembled to a tenfold number of objects. A functional decomposition is presented to support this assembling. In doing so, objects and knowledge about component properties can easily be added, modified or deleted.

Chapter 5 includes the various knowledge acquisition methods for extracting submarine design models.

Chapter 6 describes the design knowledge. The knowledge is viewed from a sizing, balancing and performance perspective. The sizing knowledge includes models which determine the contribution to both the ‘supply’ side and the ‘consumption’ side of the space, weight and energy balances. Much research effort is given to models which can determine the consumption of space in the submarine based on space properties of objects allocated to the space. Following the contributions to the different balances, each balance of a concept is examined for viability. The performance parameters of viable concepts are discussed, using the same functional decomposition as presented in chapter four. Note, at this stage of the development process both the cost and manning balances are no further discussed, due to restricted resources and lack of available data.

Chapter 7 contains the issues which arise during the implementation of the algorithms. Guided by the references [vd Nat 1994/1995], first a justification is addressed of using knowledge-based technology as a key to developing the design tool, now called
SUBCEM. This is followed by an explanation of the architecture of the tool, which includes a description of the object algorithms and the ways they interact. Finally, guidelines are given for the implementation strategy. The aim of these guidelines is to control the quality of the implemented knowledge and to reduce the efforts in maintaining the tool.

Chapter 8 answers the practical questions: will it work, and what problems can the application solve in the organization? Case studies demonstrate how the SUBCEM is used to size existing boats and how it can investigate specific design problems.

The final chapter draws a number of conclusions from the experiences with these applications, including some limits on its applicability. To increase the usability of the model, recommendations for further research are given.

What cannot be found in this dissertation is anything from the field of knowledge-based tool development. This subject is treated in a number of references [van Hees, 1997] and [Guida, 1994].
LITERATURE REVIEW ON SHIP DESIGN PROCESS

Design = ... the intellectual attempt to meet certain demands in the best possible way
G. Pahl

In this chapter, design processes for (ship-) design as found in literature are discussed. The discussion of the current design methods starts with the description of general strategies applied in design. Various strategies of design are summarized, however it is worth knowing that none of them is able to describe the total design process. Instead of focusing on a specific strategy of the design process, this chapter attempts to acquire a method involving several strategies for the entire process. A promising design method, using concept exploration models, is discussed. Current concept exploration models assist the designer by exploring trends over a range of design characteristics. Although the method can be applied for surface ships, it shows limitations. A new method for concept exploration is presented, which applies several strategies which are not included in the existing methods.

2.1 The Design process

Engineering design can be looked upon as a process which transforms an operational need into a design description that satisfies this operational need and that submits sufficient information for subsequent stages such as tendering, detailed engineering or manufacturing. This process can be viewed from different perspectives. First the process is viewed from the types of strategies that can be distinguished, second it is viewed from the types of tasks which are performed.
2.1.1 Design strategies

The design strategy defines the plan used to solve a design problem. In literature different strategies can be found, such as recursive three stage model [Coyne, 1989], top-down versus bottom-up model [Guida, 1993], problem decomposition, constraint satisfaction [Tong, 1992] and case-based reasoning.

Three stage model

The three stage model assumes that the design process can be divided into three main stages: namely formulation, synthesis and evaluation [Dym, 1991]. Design formulation involves identifying the requirements with associated operational conditions from defined functional specifications. Design synthesis is concerned with creating one or more alternative design descriptions. Design evaluation is the last phase, in which is checked whether the design description is valid, or in other words whether the design has performance values that match the initially formulated performance criteria.

The three stage model shows two important characteristics of the design process. First, it shows the iterative nature of design process: formulation is the first stage in this model, it does however not imply that from the beginning, the resulting performance criteria are complete and consistent. Criteria are usually refined during the process, which leads to synthesis of new (improved) design descriptions. Second, this model shows the recursive nature of the design process: depending on the required level of detail the design descriptions characterise more components. If the required level of detail can not be reached, new formulations are brought to light and the same three stages are repeated at the more detailed level. Figure 2.1 shows these two characteristics.

![Three stages model](image)

Figure 2.1 "Three stages model" showing formulation synthesis and analysis iteratively and within synthesis recursively

A typical example of the three stage model is the ship propulsion design process. The formulation stage of this process defines the propulsion criterion: maximum speed in surfaced condition. To meet this criterion, the synthesis stage creates a description of a propulsion plant, with a defined effective propulsion power output where the size of the plant is limited by the hull. The evaluation stage determines the maximum speed, based on the described hull and propulsion plant properties. This process can be repeated until the ship satisfies the maximum speed criterion. When individual components of the propulsion plant have to be designed, new performance criteria can be defined for these components followed by synthesis and evaluation.

Top-down and bottom-up model

The top-down and bottom-up models describe ways to assess a solution by using the solutions of sub-problems. Top-down models are first making assumptions for solutions
of sub-problems, these solutions are used for transforming specifications into a complete design description. This description is then used for transforming the specification of a sub-problem into a more precise description, generating a waterfall of transformations. This model forces the complete solution to be stated prior to its accomplishment.

The bottom-up models are guided by known partial solutions to relevant sub-problems. These answers are checked on usefulness for the complete solution. This model forces the partial solutions to be stated prior to its accomplishment.

The top-down versus bottom-up models show an important characteristic of the design process, that problems can be arranged hierarchically. Depending on the model used, first some attention must be given to the overall solution, or first sub-problems are solved.

A typical example of the top-down model applied in submarine design is a strategy which starts with an estimated overall space form and size. In [Burcher, 1994], first an estimate for the overall space of submarines is based on payload demand in terms of weight, space and services. After estimating these overall values, a geometrical (shape and size) and topological realization (relative position) of the boat’s components is made by sizing and locating them in the boat. Consequently, as the design progresses, the level of detail describing the components increases.

A typical example of the bottom-up model is a strategy with starts with sizing individual components, which can be located in a design. Depending on the component demands and topological realization of the boat, the overall boat’s geometry is determined. Consequently, as the design progresses the level of detail describing the overall boat increases.

Problem decomposition

The problem decomposition model assumes that the design process can be divided into three main stages: divergence, transformation and convergence. The divergence stage is concerned with breaking a problem into pieces and defining specifications for each of these sub-problems; the transformation stage transforms the specifications of a subproblem into a design description and the convergence stage involves putting the pieces together in a new way.

The problem decomposition model shows an important characteristic of the design process; that it is unnecessary for a design problem to be formulated completely before synthesis can begin. If all necessary information is available at the start of a sub-problem, synthesis to solve the sub-problem can be carried out.

A typical example of problem decomposition is the sizing of space for components. First, the selection of components are broken down into groups of components, each specifying a demand for space. Then the size of the required space is determined on basis of space requirements of the components. Finally, the size of the available space is calculated, this space is dependent on the location, size and form of the space in which the components are located.
Constraint satisfaction
The constraint satisfaction model assumes that the design process can be represented by directing 'un-directed' graphs, where nodes represent properties (or parameters in numerical relations) and arrows represent the relation between them [MacCallum, 1982][Serrano, 1992]. Figure 2.2 shows an example of these graphs. If design properties are used in more than one relationship, the set of relations can be represented as an undirected network. 'Undirected' implies that the dependency between the properties can be in either direction.

![Diagram of cycles and strong components](image)

**Figure 2.2 Cycles (bold arrows) and strong components (broken lines)**

Given this network representation, algorithms providing a design description can be considered as a process of transforming an undirected network into a directed network. Depending on a defined problem, a path has to be found between the unknown and known properties. A part of the path is found when an unknown property is assigned to a relation, in which the other properties are (or can become) known. Finally, these paths represent a directed network, which is: consistent (no conflicts or redundancies) and complete (no unconstrained degrees of freedom).

Within a path, so-called 'cycles' and 'strong components' can exist. A part of a path becomes a cycle when the first property of the path and the last correspond to the same parameter [Serrano, 1992]. In figure 2.2 the arrows show three cycles: A-F-C-A, B-D-G-B and D-G-D. A cycle represents a set of properties, which are coupled and can only be determined simultaneously. Note that a cycle can be part of another cycle. A strong component contains properties which are accessible by all other properties within the same strong component but not by properties belonging to other strong components. Using this definition: a strong component represents the smallest set of relations, which can be solved simultaneously or can be used to detect inconsistency. Recognition of these special parts of a path are important for efficient evaluation of the network. In Figure 2.2 the broken lines show the strong components.

A typical example of constraint satisfaction is the strategy of multi-directional constraint propagation [Sekimoto, 1989]. Constraints in this strategy represent numerical design knowledge, using equalities and inequalities. During the design process, each constraint is evaluated and the status is one of the following: satisfied, violated, not used (yet). If satisfied the constraint propagates multi-directionally to 'not used' constraints by its related design parameters. Propagating to 'not used' constraints is equal to the above representation of directing the undirected network. Violation during the propagating occurs when inconsistency between the design parameter is detected.
Defining new specifications can clear the violation, causing re-propagation of the constraints.

Numerical optimization can be applied to search in the directed network from an initial solution to more optimal solutions, with respect to a performance parameter or a merit function. There are many mathematical algorithms to optimize non-linear, multi-dimensional, non-continuous functions. The majority of these functions use a form of gradient descent to direct the search. Gradient information can be provided by gradient functions, but if these are not available the information is generated by finite difference techniques.

Case-based reasoning

The case-based reasoning model assumes that the design process accommodates a selection of solutions from previously successfully solved design problems which are stored as cases. The conditions for re-use are explicitly stated by problem descriptions associated to the case itself. Retrieval of applicable case(s) is based on close similarity between these problem descriptions.

The case-based reasoning model shows an important characteristic of the design process, that previously solved problems contain valuable information, which can be used in present problems.

A typical example of case-based reasoning is the so-called parent-ship strategy. In this strategy the designer selects an existing, built ship which most nearly matches the operational requirements. Knowledge about previously generated designs can also be used for numerical optimization, as it supports the selection of a potentially good design point. A good starting point greatly reduces the computational requirements compared to techniques using numerical optimization alone. In literature several examples are found using these techniques, such as [Netten, 1993] for composite structures, [Dai, 1994] for marine thrusters.

2.1.2 Design tasks

Design tasks are essentially problem solving tasks, involving transformation of a functional specification into a design description.

The transformation tasks can be classified into three different types: routine, exploratory and creative [Guida, 1993][Tong, 1992]. Note, these terms are used in reference to the tasks, but not to the resulting design. Using this observation, an innovative task can produce a routine design with respect to the current market, but also the opposite can occur. The type of task is characterised by the amount of available knowledge.

The task is called routine when the objective of the design task is to solve a design problem by tailoring existing design solutions to a new design. Sufficient knowledge is directly available for converging to an acceptable design. ‘Directly’ in this respect means that a single well-structured pass through the transformation process is sufficient to produce a valid design which solves a problem. An example of this process is the
sizing of a propeller for a defined thrust, revolution rate, number of blades, and speed of advance. This process uses for instance the B-screw series [Oosterveld, 1975].

The task is called exploratory when the objective of the design task is solving a design problem in which a single pass through the transformation process is not sufficient to produce an acceptable design. The result requires adjustment of the problem formulations during the design process. As a result, both the problem and the solution co-evolve.

An example of this process is solving the ‘intercept’ problem for a surveillance submarine. To fulfill the intercept capability, the submarine has to travel towards a target. This capability defines a ‘speed endurance relation’ design problem, because depending on the intercept angle a certain speed must be achieved for a certain time. The intercept angle is the angle between the chosen submarine’s track and the shortest possible track to the target, see figure 2.3 [Prins, 1988]. This relation has a major impact on the design description of the submarine, as both increasing speed and time at which this speed can be sustained require larger components. To accommodate these larger components, the size of the submarine has to increase. However, for a given propulsion power the speed is mainly dependent on the size of the submarine. Thus, increasing the submarine size means decreasing the maximum achievable speed for a given propulsion power. Furthermore, decreasing speed results in an increasing time to intercept. Consequently, all these relations have to be analysed continuously during the exploratory design, to determine a valid design description which can fulfill the intercept function.

![Intercept diagram](image)

**Figure 2.3** Intercept diagram according to [Prins, 1988]

The task is called creative when the objective of the design task is solving a design problem for which not sufficient knowledge is available, given the current understanding of the problem. An typical example of this kind of tasks is described by
Jackson [1989]. In this reference design tasks are described to solve the ‘target detect ability’ problem.

To fulfill the target detection function the submarine has to detect the noise of a target submarine. The noise is detected by hydrophones. The capabilities of the hydrophones are, according to [Jackson, 1989], mainly dependent on the amount and the distance between them. A highly capable noise detecting submarine requires an ‘outer hull area-volume ratio’ which is much larger than in conventional submarine designs. The reference describes a disc-like outer hull shape, with a ring stiffened toroid plus spherical main-structure. The shapes described for the structure are much different from the presently used shapes. Existing knowledge about sizing structure and calculating propulsion performance are not valid. Thus, new knowledge has to be developed for solving these kind of problems.

2.2 The Concept Exploration Model

In recent years, the Concept Exploration Models have shown a promising method for supporting the conceptual design phase of ships. A considerable number of papers have been produced on this subject. One of the first models of this kind was introduced by Eames [1976]. This paragraph reviews the limitations of the existing models and describes the features of a new model to overcome these limitations.

2.2.1 Existing Concept Exploration Models

The ‘traditional’ Concept Exploration Models are typical straightforward three stage models, which are, for example, described by Eames [1976] for frigates, Nethercote [1982] for SWATH ships, Schaap [1990] for patrol vessels, Georgescu [1990] for multi-purpose ships, and MacGregor [1990] for underwater vehicles. ‘Traditional’ in this context refers to models in which design problems are implemented as structured problems, according to the three stage model of formulation, synthesis and evaluation stages into respectively pre-processor, processor and post-processor.

The pre-processor defines input values for a fixed set of functional requirements and exploration definition parameters. The input contains independent design parameters and optional parameters. Independent parameters are defined by a range of values, for ship design typical independent parameters are hull form parameters. Optional parameters are defining operational objectives and other options, for ship design these can include cruise speed, endurance, number of complement, but also number of decks, superstructure length etcetera.

The batch processor represents the synthesis model, transforming the specifications for each set of exploration parameter values into a design description. Characteristic for the processor is the fixed problem strategy containing a directed network of design relationships, as defined by the constraint satisfaction model. ‘Directed’ implies that information can flow in one direction, which is fixed by the design problem, as discussed in the previous paragraph. The relationships in these models contain only
numerical knowledge. Mass- and volume-balances of the ship do not contain geometric or topological information. To overcome this lack in knowledge representation a general arrangement is selected and its dimensions are described by parameters. By specifying a range of geometrical and/or requirement parameter values, a large number of designs are systematically generated. These designs together define a so-called design-space.

The post-processor usually provides a tool to present the calculated performance parameter values, providing knowledge about the relationship between in- and output parameter values. Constraints can be defined for rejecting impractical cases and merit functions for ordering the calculated solutions for the problem. Merit functions rank design descriptions on a basis of weighted performance scores. Normalising the weighting factors, to a value between 0 and 1, indicates the relative importance of performance [Georgescu, 1990]. The performance itself can also be normalised to achieve relative scores [Hooper, 1981], having the advantage that the outcome of the merit function is also a value between 0 and 1. Consistent selection of relative importance factors and normalised achievement is important when a large number of variables is involved. Relative importance factors can be presented into a matrix, in which each element compares the relative importance to another element. The consistency can easily be checked, because the determinant of this matrix must be zero [Buxton, 1992]. In real life however, the level of consistency is difficult to achieve.

Further refinement of the merit function is proposed by using multi criteria decision making techniques. In these techniques, performance variables are decomposed into a performance hierarchy. For example, the overall effectiveness of an offshore patrol vessel is decomposed into interception and patrol capabilities, both performance variables are further decomposed into speed, endurance, sea keeping and habitability performance. The alternative design descriptions are ranked for each performance variable at the deepest level of the performance hierarchy, such as for instance speed and endurance. For each design description the performance values are multiplied by the related weight factors of the performance variable. This process is repeated for each level in the hierarchy, until the performance value at the highest level is applied, ranking the alternative design descriptions.

The design task performed by the traditional Concept Exploration Models is characterized by routine problem solving. These models generate a large number of design variations in a reasonable time by incrementally changing one or more requirement values. The results of these concept variant studies are used for several investigations such as. selection of an optimum starting point for following design stages, studying the effect of an modification or checking published data.

Another characteristic for the Concept Exploration Models is that it does not contain any kind of optimisation procedure. Optimisation procedures are not included for two main reasons. Firstly, design knowledge contain many non-linear and/or non-continuous relations, causing problems for computing the derivatives and finding the maximum of the objective function. Secondly, the designer wants to know the robustness of the
optimized solution. A solution is robust when the optimum is not sensitive to a change in the design description. The sensitivity can be analysed by determining trends of performance values for all kinds of variations in the design description rather than the trend along a narrow path to an optimum. To support this analysis a large number of designs must be evaluated. The final question “how does the designer pick the best design” is not answered by the tool, but remains to the designer.

2.2.2 SUBmarine Concept Exploration Model
The design task to be performed by a submarine conceptual design tool is characterized by exploratory problem solving. Performing this type of design task requires continuous revision of the initial design problem as the solution evolves. The traditional Concept Exploration Models had two major limitations, which made them inadequate for performing the exploratory problem solving task in submarine design. The first limitation is the adoption of a design model which answers one or more specific design questions based on a fixed set of input values. The client has many individual requirements which have large effects on the outcome of the design process. A directed network approach is not capable to handle these individual requirements. Input and output of the design models must be adjustable and/or new submarine design knowledge must be added or modified.

The second limitation is the single representation format of all design knowledge in numeric algorithms. Specific descriptions of the internal arrangement of submarines are not possible using only numeric algorithms, because geometrical and topological knowledge are excluded. For submarines, the internal arrangement has a large impact on the feasibility of the boat.

To overcome these limitations a fundamental new way of structuring the model and its implementation is required. This new way of working is briefly illustrated below.

Undirected network approach
The approach of undirected network is an adequate way of coping with design problems. The main characteristics supported by this approach can be summarised as: proper problem decomposition, use of various knowledge sources, and accessible partial results during the problem-solving process enabling reformulation of problems.

Problem decomposition
Ideally a design problem is reduced by problem decomposition into a collection of independent sub-problems, for which the solution can be determined (bottom-up model). The undirected network approach supplies a structured way of storing the knowledge about the sub-problems and their connections. The solution of the overall problem is a combination of partial solutions. The design process can thus be considered as a simple assembling of solutions available in the domain of interest. This ideal situation is in practical design problems not always valid due to interrelations between the sub-problems. For example, requirements for two or more sub-problems, can cause possible conflicts between the performance values. This can be illustrated by the sizing problem of the Main Electric Motor and Battery. The electric motor
commutator is sized using a requirement for number of armatures and a maximum voltage at the armature terminals. The battery is sized using a requirement for number of batteries and number of battery cells in series per battery. For burst condition, when the armatures are in parallel and batteries in series, the maximum delivered voltage by the batteries at the terminal of the armatures should not exceed the maximum design voltage for the electric motor, otherwise a conflict occurs.

**Various knowledge sources**

The submarine design knowledge is based on various knowledge sources including empirical knowledge and ‘first principles’ knowledge built on physics. Both represent design expertise in the particular application. The undirected network approach makes it possible to switch from a model based on one kind of knowledge to a model based on another kind. This feature ensures that the most appropriate model is used for a specific design problem.

**Reformulation of problems**

In general, submarine design activity can be characterised as exploratory, as the strong dependency between the components require almost total re-design when some requirements are changed. During the design process the designer proceeds by selecting sets of well-understood knowledge and providing specifications for which the boat has to be designed. These specifications can be provided at any level of detail, so it can be at the overall boat level but also at an individual component level. During the problem solving, intermediate results are evaluated and can be used to direct sub-problems, requiring new choices for requirement parameter values. The choices can be stated in functional terms, but can also be specified by a system’s components that have to be installed in a new ship. In the nature of exploration, criteria for directions continually emerge, as the context of the design shifts by changes in the designer’s perspective. The undirected network approach offers features which support the transformation of all defined specifications into a consistent and complete design description.

**Representation of design knowledge**

Design problems for submarines can not be solved without using all the relevant knowledge sources on the application at hand. Numerical knowledge sources are relevant for sizing, balancing the energy, manning and cost and for predicting the performance of a balanced boat. Geometrical (shape and relative size) and topological (relative position) knowledge sources are relevant for balancing the space and weight problems.

**Numerical knowledge**

Numerical knowledge is prominent in ship design. Initially, numerical models are built which allow the sizing and performance parameters to be estimated. In many cases, as the design proceeds, more precise numerical models are used predicting the parameters more accurately, and/or producing more detailed design descriptions.
**Geometric and topological knowledge**

To study the feasibility of the submarine’s space balance, space cannot be considered only as a numerical value of volume in the submarine, as it also implies other dimensions of space, such as area, length, width and height. The space of a submarine is defined as an assembly of physical dimensions defining size and shape of the space within the submarine and the components. Typical for a submarine are the non box-shaped volumes. Describing these shapes requires geometric properties about the spaces. However detailed information about the geometry and topology is not available at the feasibility stage of the design, as it requires lay-out drawings. To overcome this lack in information, the spaces are divided into a few types. Each space type is described by a limited number of geometrical properties. Using these properties, the required and available space can be balanced, taking all space dimensions into consideration.

To study the feasibility of the weight balance of a submarine, weight cannot be considered only as a numerical value of mass and volume of displacement, but also includes their centroids. To determine the centroid of the boat requires topological knowledge about the components in the submarine. The centroids of mass and volume of displacement can be measured in three orthogonal directions relative to a fixed point. Important for a submarine are the longitudinal and vertical centroids, which are used to determine respectively the longitudinal and transverse static stability.

There is an extensive interaction between the numerical and geometrical/topological knowledge. The exploratory problems in the submarine design process cause a continuous manipulation of size, shape and arrangement of components affecting the performance of the boat. The ability to link the different types of knowledge, enables the designer to investigate a design problem more extensively.

### 2.3 Conclusions

In literature, many different design strategies are found. A combination of these strategies using a Concept Exploration Model showed the most promising method for solving exploratory design problems. Two major limitations for submarine application arose during the evaluation of the existing Concept Exploration Models: first, the existing models can only answer one or more specific design questions based on a fixed set of input values and second, the existing models contain only numerical design knowledge. To overcome these limitations the undirected network approach and integrated use of numerical, geometrical and topological knowledge should be embedded.
3

OVERVIEW OF SUBMARINE DESIGN KNOWLEDGE

*Expert designers know the form of the answer when they begin a design; design involves manipulation of these forms until the problem constraints are specified*  
J.F. Koegel

Design problems can only be solved when all the relevant design knowledge on the application is understood and represented. This chapter addresses the design aspects of (military) submarine design. The first paragraph of this chapter starts with an introduction to the submarine design process in which three sub-processes are distinguished: sizing, balancing and performance calculation. Many references have already been presented on these sub-processes [Arentzen, 1960][Allmendinger, 1990][Jackson, 1992][Burcher, 1994]. Each of these references describe the submarine design knowledge in more or less detail. This chapter structures the existing knowledge in a way that it provides an insight into the submarine design problems and the knowledge needed to solve them.

3.1 Submarine design process

The design process starts when it has been decided that a submarine is required to perform a defined mission. A *mission* is a description of what the client wants to accomplish, under specified conditions. The result of the mission description is a set of requirements acceptable to the client. Users in this definition can be of industrial, military, scientific or recreational origin, who want to fulfill one or more categories of underwater missions like: transportation, detection, tracking, inspection, survey, search, rescue etcetera. These mission descriptions are the basis for defining the functions that the submarine must fulfill. Eight main functions are distinguished: (1) Carrying

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrying platform</td>
<td>Providing a structure which carries and distributes mechanical loads to which the boat is subjected. Loads are for example caused by hydrostatic pressure, earth's gravitational field, hydrodynamic forces or collision forces.</td>
</tr>
<tr>
<td>Manoeuvring</td>
<td>Power to move the boat in any of the six degrees of freedom of the boat, including the ability to submerge and to surface.</td>
</tr>
<tr>
<td>Energy supply</td>
<td>Containment, transformation and supply of a required amount of energy, such as electric-, hydraulic-, or pneumatic energy.</td>
</tr>
<tr>
<td>Ship control</td>
<td>Monitoring performance of the boat and adjusting control systems when deviations from a required performance occur.</td>
</tr>
<tr>
<td>Navigation and Observation</td>
<td>Determination of position, course and speed of the boat and other platforms.</td>
</tr>
<tr>
<td>Communication</td>
<td>Communication with the in- and external environment.</td>
</tr>
<tr>
<td>Life support</td>
<td>Provision of facilities for life comfort and protection.</td>
</tr>
<tr>
<td>Special functions</td>
<td>Handling and control of mission systems determined by the functional requirements as specified by the user-defined mission.</td>
</tr>
</tbody>
</table>

Each main function can only be fulfilled by an assembly of components. The relation between main functions and components can be described using existing terminology. For practical reasons, the most frequently used terminology 'Ship Work Breakdown Structure' (SWBS) [NavSea, 1985], is chosen to make the analysis of the available data easier. Applying existing terminology is practical, as it supports the completeness of the defined functions and it corresponds to existing demarcations. Breakdown structures include several levels to describe a boat. At the highest level the breakdown structure contains the main functions. At a lower level each function is divided into a number of sub-functions. Each (sub-)function must be fulfilled by at least one system. At the deepest level of interest for the designer the functional and physical identification are identical. This deepest level is defined as a component [Vucinic, 1994]. The description on this level identifies the capabilities that have to be performed by an installed component. Within the SWBS decomposition the components are defined at the fourth level. Appendix A contains these components, however they are re-ordered to the above given main functions. If components serve dual or triple functions, the item is always classified by its primary function. For example a battery has the primary function of energy storage within the main-function energy supply, although it may be part of the ballast function within the main function carrying platform.

During the design process, the decomposition is used to control budgets. Budget control formulates the amount of 'supply' and 'consumption' of five component properties:
space, weight, energy, manning and cost of each allocated component. The words ‘supply’ and ‘consumption’ are used to illustrate that components can both add and subtract an amount of each property to respectively from the boat. The values for the budgets are determined during the so-called sizing process. Once the budgets are set, two checks are made. The first check is a balancing process, to ensure that the total amount of added property values is larger than the total amount of subtracted property values. The second check is a performance calculation process, to ensure that the (measurable) capabilities that various components must possess under specified conditions are larger than the capabilities pre-described by the mission specification. Both the sizing process and the checks made within the submarine design process are described in more detail below.

3.2 Submarine sizing

In the submarine sizing process the components, structure and spaces of the boat are sized, based on component capabilities, which are defined for a specific operational and environmental condition. Within the sizing process limitations on the dimensions of components also have to be considered. A typical example of these limitations is the hatch dimensions used for access.

For each main function the capabilities and constraints are briefly discussed and examples are given of current available components.

3.2.1 Carrying platform

The carrying function is defined as ‘providing spaces for allocating components in the submarine’. The spaces are constructed by primary and secondary boundaries. Primary boundaries enclose a volume of air at atmospheric pressure and have a capability to withstand a defined differential pressure between seawater pressure and atmospheric pressure. Secondary boundaries have a subdivision and support function.

Primary boundary

Sizing the primary boundaries involves determining shape and dimensions of structures capable to resist one or more types of load. Load types can be divided into static, cyclic and dynamic loads.

The static load is the external lateral load generated by the water pressure at diving depth. The dimensions of the primary structure are determined by the maximum static load due to a pressure difference between seawater pressure at collapse depth and atmospheric pressure. In normal operation the deepest level for diving is the deep diving depth. The duration of deep diving is considered to be short enough that creep can not be a cause for collapse. Diving below this depth occurs only when the submarine is forced through a misadventure, such as an overshoot manoeuvre.

As submarines are frequently diving and surfacing, the static load can become an irregular cyclic load. This load causes low cycle fatigue when alternating tension and compression stresses occur in parts of the structure. Only a small part of the primary
structure is expected to be subjected to this type of load. Care has to be taken in the design of these structural parts, to avoid high stress and strain levels. In consequence, fatigue can cause local adjustments in the primary structure design.

*Dynamic loads* are generated by, for example, shock waves from standoff underwater explosion. Under these very fast dynamic loads the primary structure much less stiff than under slow varying loads. As a consequence, the primary structure can withstand much higher dynamic loads than static loads. However, local hard spots must be avoided in the primary structure, to avoid high stress levels. In consequence, dynamic loads can cause local adjustments in the primary structure design.

![Diagram of underwater structure](image)

**Figure 3.1** Boundaries primary (bold lines) and secondary (fine lines) types

Typical examples of current components fulfilling the primary boundary function efficiently are (multiple) spheres and/or ring stiffened cylinders. Efficiency, in this context, is measured by the ratio between enclosed volume and mass of the structure. Figure 3.1 shows these components in bold lines. Spheres can fulfill the function most efficiently, because its shell is uniformly strained in all directions under external lateral load. However, a spherical shape has its drawbacks, when considering the filling of components having box-shaped volume. Next to a sphere, the most efficient primary-structure is a ring stiffened cylinder with domed enclosures at either end. This shape is structurally less efficient compared to the sphere, since a cylinder does not have a geometrical stiffness in the longitudinal direction. Cross sectional shapes of the primary structure departing from the circular cross-section decrease the efficiency due to extra ring bending moments.

In practice a pure cylindrical shape with dome ends is not applied, because the cylindrical shape often uses truncated cones to fit the primary structure more to a streamlined shape and deep frames or transverse bulkheads to reduce the overall (collapse) length of the cylinder. In a cone, the transverse bulkhead is commonly located at the small cylinder end, as this location is from structural point of view
preferable: the thrust along the axis from the pressure on the transverse end-bulkheads, acts to push the junction at the small cylinder end inward, which is concurrent with the shrinking of both cone and cylinder.

Secondary boundary
Sizing the secondary boundaries involves determining shape and dimensions of structures capable to separate the space within or outside the primary structure. Aspects affecting the separation are installation, maintenance and protection of components, reduction of total fire or flooding risk of the boat, provision of escape spaces in case of partial flooding, or isolation of noise and heat sources.

Typical examples of current components fulfilling the secondary boundary function are decks, bulkheads, appendages and outer hull shell. Figure 3.1 shows these examples in normal lines.
Decks and transverse bulkheads divide the space in the primary structure into respectively a number of vertical and horizontal spaces. Special features for these, so called, inboard boundaries can be defined. Typical examples are:
  • Providing mechanical support to foundations/mountings of installed components.
  • Withstanding a defined pressure to provide volume from which the crew can be rescued in case of a flooding.
  • Reducing the transmission of noise and vibration to decrease the acoustic signature outside the boat, and to improve the habitability inside the boat.

Outer hull and appendages divide the space outside the primary structure into respectively a streamlined envelope around the primary structure and structural items extending beyond this streamlined envelope. For the streamlined envelope a small curvature is preferred, as this decreases the pressure drag and moves the position of the transition zone downstream, away from the forward end of the envelope. The transition zone is the area along the envelope where the laminar flow becomes turbulent. The position of the transition is for example important for noise 'transparent' sonar windows, which can be best located in a laminar region with low self generated flow noise.

3.2.2 Manoeuvring
The function manoeuvring requires components providing power to move the boat in any of the six degrees of freedom of the boat, including the ability to submerge and to surface. In this function two sub-functions can be distinguished: a hydrostatic handling and a hydrodynamic handling function.

Hydrostatic handling function
The hydrostatic handling function is defined as 'the ability to move the boat by employing static forces'. This function involves weight and/or buoyancy variations for maintaining neutral buoyancy, in all kinds of submerged or surfaced conditions during the mission. Neutral buoyancy is defined as 'achieving equality of the resultant buoyancy and weight forces and their longitudinal and transverse moments for a
horizontal and upward directed boat at rest'. Neutral buoyancy should not be maintained in the transit condition where the boat goes from floating on the surface to gliding submerged, or vice versa. When the vessel submerges the water-tight volume above the water plane will displace water and thus going from surfaced to submerged condition either the weight of the vessel has to increase or the buoyancy has to decrease.

Buoyancy is the upward force equal to the weight of seawater displaced by the completely submerged component (Archimedes principle). As the density of the seawater can change, the buoyancy of components changes as well. For this reason not buoyancy but volume of displacement is chosen as a property of the components. For present submarines the major source of volume of displacement is the enclosed volume of the primary structure. In addition to the primary structure other volumes of displacement arise from components and secondary structure located outside the primary structure.

Weight is the downward force created by the mass of the components. The determination of mass is chosen as a property of each individual component. For large components, like primary- and secondary structure, propulsion plant, or main batteries the mass can be obtained relatively easily. The difficulty lies more in the smaller components, for which reliable masses are difficult to obtain. To overcome these uncertainties the component margin-ballast is defined. Margin ballast allows for uncertainties in the design of components leading to unplanned mass growth of components, addition of new components, or shifts in centre of gravity in height and length. The location as well as the amount determine its utilization during the design. Margin ballast is hardly ever at the location of the unexpected mass growth. If the mass growth is at the aftmost part of the boat then the remaining margin ballast has to shift forward to maintain the longitudinal balance. Figure 3.2 shows this shift, it also shows that the maximum utilization along the height and length [Burcher, 1994].

![Figure 3.2](image_url)  
Figure 3.2  Amount of weight margin

The balances between weight and displacement and their moments are described in more detail in paragraph 3.3, where the submarine weight balancing is discussed. For the design condition the neutral buoyancy function is fulfilled by reducing or increasing
the weight and/or its longitudinal, vertical and transverse moments of the ballast. This ballast can either be fixed (Stability lead ballast) or variable (Seawater ballast). The ratio between the fixed and variable ballast determines the performance of the hydrostatic handling function, see paragraph 3.4.

A typical example of current components fulfilling the variable ballast function are water distribution components. These components are taking in or discharging water and are moving water in forward and aft direction in the boat. High pressure pumps and distribution piping can be used to move seawater at diving depth in and out weight compensation (or hoover) tanks. Low pressure trimming pumps and distribution piping are used to move water between the trimming tanks. Large amounts of water are discharged by blowing main ballast or (quick) diving tanks to the sea. The dischargeable part of the Main ballast water is treated as added mass in the vessel. Within this added mass approach the buoyancy remains constant and the main ballast system adds mass while diving and removes it while surfacing. Some submarine designers treat the ballast water as lost buoyancy. Within that approach the mass remains constant and the main ballast system removes buoyancy while diving and adds it while surfacing.

Hydrodynamic handling function
The hydrodynamic handling function is defined as ‘the ability to move the boat by employing dynamic forces’. This function involves lift and/or thrust variations for maintaining constant depth and course at a certain speed and the ability to change this depth, course and speed in a controlled manner. The first ability is called dynamic stability and the second, dynamic control. Both abilities are only possible when the propulsion function is fulfilled, which delivers thrust to move the boat at the required speed.

Hydrodynamic forces and moments act on the boat as a result of its motion through the water. A boat is hydrodynamically stable when it returns, without corrective actions, to its original course after a small disturbance in the external forces and moments. For hydrodynamic control, the combined forces and moments, including those from control actions, must result in a movement of the boat according to a specified path.

A typical example of current components fulfilling the hydrodynamic handling function are fixed or (partly) rotatable hydroplanes and thrusters, both are able to generate the required horizontal and vertical forces. For hydroplanes the magnitude of these forces depend on the speed of the submarine and deflection angle of the hydroplanes. For low speeds the lifting forces of the hydroplanes become close to zero. At these low speeds the manoeuvring function can be fulfilled effectively by thrust producing systems.

As mentioned above, the hydrodynamic handling function requires fulfilling the propulsion function. In the propulsion function three sub-functions can be distinguished: a thruster function, a mechanical transmission function and a driving function.
The longitudinal propulsion thruster function is defined as ‘transforming rotating into longitudinal mechanical power’. Rotating mechanical power is measured by torque times angular velocity, and longitudinal mechanical power by thrust times an achieved speed. The thrust is produced by accelerating the water flow through a thruster. Increasing the mass of water in the flow for producing the same thrust results into a smaller acceleration. Smaller accelerations cause smaller losses thus increasing the efficiency of the transformation. Not only the acceleration, but also the mean velocity on which the acceleration is brought about determines the efficiency. Higher mean velocities cause more friction, thus decreasing the efficiency. High propulsion efficiencies can therefore be reached by large thrusters in slow moving water.

A typical example of current components fulfilling the thruster function is a single axial propeller without nozzle. Important design requirements of the propulsion thruster system for submarines are: high propulsive efficiency, low (noise) signature level and high shock resistance. Sizing the propeller requires sizing a hub and sizing blades which transforms the energy in the most efficient way. The thrust and torque of the propeller depend upon the lift and drag characteristics of the sized blades. The lift on the blade is produced partly from the suction on the back of the blade and partly from positive pressure on the blade face. An important constraint for the pressure on the back and tip of the blade is the vapour pressure of water. When the pressure on the back becomes lower than the vapour pressure the phenomenon known as cavitation occurs, causing noise associated with the collapse of cavitation bubbles. The risk of cavitation can be reduced by restricting the blade pressure loading, and producing a uniform pressure distribution along the blade area.

The mechanical transmission function is defined as firstly ‘transmission of mechanical power from the driver to the thruster’ and secondly ‘transmission of the thrust from the thruster to the hull’. Mechanical power is represented by a torque with a rotation rate. Two different types of transmission are distinguished, a direct and an indirect drive. A direct drive needs an equal rotation rate of driving system and thruster system. An indirect drive enables a different rotation rate.

A typical example of current components fulfilling the mechanical transmission function are shafting, reduction gears, clutches, thrust block and couplings. Systems fulfilling a direct drive function do not require reduction gears and clutches, thereby avoiding a major source of noise and vibration.

The propulsion driver function is defined as ‘generating mechanical power’. This power is generated by transformation of an electric or another source of power. The dimensions primarily depend on the required torque and rotation rate at maximum delivered mechanical power. Low torque with high rotation rate of the drive results in a small component.

A typical example of current components fulfilling the direct driver function are DC (direct current) electric motors with the rotor directly coupled to the propeller shaft. This coupling causes a matching problem between the torque and rotation rate of the motor and of the propeller. High torque demanded at a low rotation rate needs a large rotor diameter or multiple rotors on one shaft. For a given rotation rate the size of the
rotor diameter is limited by the circumferential forces working on the windings. To overcome this limitation multiple rotors can be applied, which results in a smaller diameter, however this is at the cost of a larger length.

3.2.3 Energy supply
The energy supply function is defined as ‘containment, transformation and distribution of electric-, hydraulic-, pneumatic energy and cooling or heating’. The energy is used for propulsion and hotreload purposes. The hotreload contains all power needed to supply the consumers other than the propulsion drivers. Several operational conditions can be distinguished at which these non-propulsion systems require different amounts of energy. For each kind of energy one of these conditions determines the maximum consumption, which is called the nominal load. When this maximum consumption includes a margin for uncertainties, the energy consumption is called design load.

Energy containment function
The energy containment function is defined as ‘storage of energy which enables the supply of sufficient energy during a mission’. An important requirement for the energy storage is a high energy density, which is defined as the ratio between the energy content and the mass or volume.
A typical example of current components fulfilling the energy containment function are diesel fuel in tanks, electric energy in batteries, hydraulic oil in accumulators and high pressure air in bottles.

Energy transformation function
The energy transformation function is defined as ‘conversion of the stored energy into a required form’. Examples of these media are current at a defined (alternating) voltage, air or hydraulic oil at a defined pressure or chilled water at a defined temperature. Providing the required form involves (multiple) transformations, each having its own efficiency.
Typical examples of current components fulfilling the transformation function are diesel engines generators, hydraulic pumps or compressors. The diesel engine transforms stored chemical energy in mechanical energy. The generator transforms the mechanical energy in electrical energy. Finally the electrical energy can be further transformed by electric motors and hydraulic pumps or compressors in other energy forms. An important characteristic for these transformations is the dependency on atmospheric air, because oxygen is required during the transformation process from chemical energy to mechanical energy in diesel engines. If a transformation is dependent on air, then the transformation can only be performed in surfaced or snorking condition, otherwise air (oxygen) has to be stored onboard providing air independent energy.

Energy distribution function
The energy distribution function is defined as ‘transportation of energy from supplier to consumer’. Two types of distribution systems are defined: global and local systems. Distribution systems which transport energy along the boat are called global systems. Systems which control the energy flow, for example by dividing flows into multiple
flows, are called local systems. Typical examples of current components fulfilling the global distribution function are cables and piping, examples of local distribution systems are electric switching gears and hydraulic or pneumatic control valves.

3.2.4 Ship management
The ship management function is defined as ‘monitoring the performance of components necessary for executing the tasks of the ship and adjust the operation of the components when deviations from the required performance occur’.

The actions required for adjusting the operation of components can be divided according to the physical location and the intelligence behind the control. The monitoring and control actions can be realised at different locations: locally at the component and/or remotely from the component and/or at a central location. The last option has the possibility to leave spaces, in which the components are installed, unmanned. The monitoring and control actions require intelligence for making decisions between different corrective actions. The knowledge about the actions can be provided by a member of the crew or by a programmed device.

Typical examples of current components fulfilling the control function are: Propulsion switchboard, which controls the connections which can be made between the electric motor armatures and the batteries. These switches can be monitored and operated both locally and remotely. In addition to remote operation, automatic operation may be available. This requires automatic switching arrangements, which base their actions on required power and rotation rate of the propulsion motor. Diesel generator and battery charging system, which monitors and controls the starting and stopping process of the diesel engines in which also the inlet/exhaust systems are involved. The battery charging control system monitors and controls the battery charging current depending on the actual battery condition and available generator power. The hydroplanes steering control involves monitoring and adjusting the hydroplane angle based on the required and actual depth and/or course of the boat.

3.2.5 Navigation and observation
The navigation and observation functions are defined as ‘the capability to determine the actual position, depth, course and speed of the submarine itself and of other submarines and surface ships’. Systems fulfilling this function can be: electric, electronic, acoustic, magnetic or visual observation systems. For each operating condition one or more of these systems are used operating independently or interacting with each other. Typical examples of current components fulfilling the navigation/observation function are gyroscopic systems (e.g. gyro compass), microwave systems (e.g. radar navigation systems), acoustic systems (e.g. sonar systems), magnetic systems (e.g. magnetic compass) or visual systems (e.g. periscopes).
3.2.6 Communication

The *communication* function is defined as ‘the exchange of information’. This function can be divided into two sub-functions internal and external communication. The first type of communication exchanges information between persons on board, and the second exchanges information between person(s) onboard and on other platforms or on shore.

Typical examples of current components fulfilling the internal communication function are telephones and alarm, or announcing systems. A typical example of current components fulfilling the external communication function are radio systems for surfaced conditions and acoustic telephones for submerged conditions.

3.2.7 Life support

The function *life support* is defined as ‘the provision of facilities for comfort and life protection’.

The life comfort function implies the habitability of the submarine. This function can be divided into the subfunctions accommodation, breathing gas control, storage of provisions, food preparation and waste handling. These functions become increasingly important as the number of crew or the mission duration increases. The number of crew-members is determined by the installed components and the chosen watch system. Each component requires an amount of man hours for (emergency) control and/or corrective and preventive maintenance.

Life protection implies the protection and escape of people from a hostile environment such as a flooded compartment and against dangerous impacts of installed components, like fire and toxic gasses. Life protection can be based on protection of individuals or the boat as a whole.

Typical examples of components fulfilling the life comfort function are messes and berthing for accommodation, oxygen candles and CO₂ scrubber for breathing gas control, galley for food preparation, and garbage ejector for waste handling. A typical example of current components fulfilling the life protection function are escape suits for individuals and fire fighting system for the boat as a whole.

3.2.8 Special functions

The *special functions* are defined as ‘the handling and control of mission systems’. Handling systems involve the storage, transportation and launch of components required to fulfill the mission. The control system involve the monitoring and guidance of these components. For a offensive/defensive military submarine the most important function is fighting. To fulfill the fighting function the boat must be able to communicate, detect threats, track targets and engage targets. Typical examples of current components fulfilling the military communication function are: VLF radio system, Link 11 system, IFF transponder system and crypto system. Typical examples of components fulfilling the threat detection and target tracking function are: mine avoidance sonar, towed array sonar, intercept sonar, ESM system and tactical data handling system. Examples of components fulfilling the target engaging function are: weapon handling and control systems such as torpedo stowage, shifting and reloading system, torpedo tubes, torpedo control and interface equipment.
3.3 Submarine balancing

For a design to be viable, it should be balanced on five component properties: space, weight, energy, manning and cost. The space and weight properties have a special relationship. The space is balanced when the amount of available space is greater than or equal to the amount of space necessary for allocating the components. The weight is balanced when the buoyancy and the weight of the vehicle and their moments are equal. Both balances have to be achieved, leading to the ultimate question in submarine design as formulated by Burcher [1994]:

"Does a submarine have to be of a certain size to provide enough buoyancy to support its weight or does it have to be of that size to provide enough space for its content?"

Balancing the other properties can be done separately. The energy is balanced when the power and energy storage onboard is greater than or equal to the maximum required power and energy consumed during a mission. The manning balance is achieved when the number of available man hours during a mission is greater than or equal to the number of required working hours. The cost balance is achieved when the cost of a vehicle is lower than or equal to the financial budget. Each of these balances is briefly discussed.

3.3.1 Space/weight balance

The answer to the question, put forward in the introduction of this paragraph, is dependent on the static forces. For a vessel at rest in a submerged condition, the only static-forces acting on it are caused by hydrostatic pressure and the earth’s gravitational field. Both are working in the vertical plane, therefore the equilibrium in only three degrees of freedom have to be studied: resultant forces along the vertical-body axis and resultant moments about the longitudinal and transverse-axes. In other words the weight of the boat must be equal to the weight of displaced water, and the centres of gravity and buoyancy must be in the same vertical line. To create a restoring moment when the boat is heeled or trimmed, the position of the centre of gravity must be below a defined distance of the centre of buoyancy. This constraint is called stability constraint. The effect of the magnitude of this distance on the ship control function performance of the boat is described in the next paragraph.

The ratio between the total weight of the boat and displaced volume in submerged condition is called the overall density. If during the design process the overall density is smaller than the density of seawater then the design is called space driven otherwise it is weight driven.

In a space-driven design the balancing is initiated by space estimates and followed by the weight balance. For a submarine dimensions of space are besides volume, also deck area, length, width and height. Therefore within the available space the shape becomes
as important as its amount. As a result components requiring not only volume but also
deck area, height, width and length are more difficult to allocate than components
requiring only an amount of volume.

For a space driven design the weight balance is achieved by defining stability ballast.
Stability ballast is utilised as an additional amount of weight, allocated to balance the
weight versus buoyancy forces and moments and to fulfill the stability constraint. If the
required amount of stability ballast becomes less than zero and/or its location becomes
close to the extreme ends of the boat or even outside the boat, then the design is no
longer space driven but becomes weight driven.

In weight-driven design the balancing is initiated by weight estimates and followed by
the space balance. Weight and buoyancy forces are first balanced followed by the
balance of their moments. While the weight force is larger than the buoyancy force,
additional volume of displacement must be created by defining extra amount of space
in the volume of displacement space, which is however not required for allocating
components. As a result the volume in the boat becomes larger than required by the
allocated volume of the components.

While the weight moments are not equal to the buoyancy moments or the stability
constraint is not fulfilled then the location of the stability ballast must be shifted. When
the location of the stability ballast becomes close to the extreme end of the boat(s), then
both the amount of stability ballast and volume of displacement must be increased. As
a result the volume in the boat becomes larger than required by the allocated volume
of the components.

A given space driven design can become a weight driven design when the overall
density of components increases. An example of increasing density is a growing
capability of the primary structure, which requires larger structural dimensions while
its total volume of displacement is not increasing. On the other hand a given weight
driven design can become a space driven design when the overall density decreases.

3.3.2 Energy balance

The energy balance contains four different sub-balances according to the main forms
of energy: electric, hydraulic, pneumatic, and heat balance. All energy consumers and
suppliers can be part of one or more of these sub-balances. The balancing of energy is
achieved when the amount of required energy in each operating condition can be
supplied during the complete mission of the submarine. The operating conditions of the
boat define normal and extreme conditions, which occur during a mission. For example,
the following conditions are typical conditions for a military mission: full, transit,
patrol and survival conditions, which can occur for submerged, snorking and surfaced
situation. Patrol and transit define normal operating conditions, full an extreme high
load condition and survival an extreme low load condition.

3.3.3 Manning balance

The manning balance considers on one hand the required number of man hours per
watch-period to operate and maintain the submarine and on the other the amount of
available man hours during the watch-period. The required total number of man hours is, similar to the energy balance, dependent on the operating condition.

3.3.4 Cost balance
The cost balance considers both the required budget for life-cycle cost and the available budget. The life-cycle costs include installation cost, material or component cost, operating cost, maintenance cost, and decommission cost.

3.4 Submarine performance calculations

In the submarine performance calculations, the boat performance characteristics are determined and compared to the mission requirements. Performance characteristics measure the satisfaction of functional specifications, for a defined operational and environmental condition. Each submarine has a set of performance variables which can be ordered to their relative importance depending on the mission tasks. For this reason one single set cannot be defined. In this paragraph the performance variables according to the submarine functions are discussed as an example of a defined set.

3.4.1 Carrying platform
The most important performance parameter which can measure the satisfaction of the components fulfilling the carrying platform function is the package efficiency of the spaces within the platform. The package efficiency is defined as the ratio between the maximum amount of space and the occupied amount of space. Space in this definition can have any dimension, such as length, area or volume, and can include or exclude the space between the frames of any structure.

The maximum achievable package efficiency is dependent on the shape and size of the cell. Figure 3.3 presents the results of an area comparison for two, three and four deck compartments. The figure shows steps in the effective deck area (with a height larger than 2.3 [m]) per unit volume when a deck is added.

![Figure 3.3 Package efficiency of cross sectional area for different number of decks](image)

Figure 3.3 Package efficiency of cross sectional area for different number of decks
The package efficiency is also limited by the accessibility of components. A relatively high space efficiency will reduce the accessibility and increase the installation costs. The package efficiency is not always limited, for example it can become close to one when the space is used for tankage. A minimum package efficiency cannot be defined. However, a relatively low efficiency will increase the dimensions of the design and therefore the costs.

3.4.2 Manoeuvring
The most important performance parameters of the components fulfilling the manoeuvring function are the hydrostatic ship control parameters and the hydrodynamic ship control parameters.

Hydrostatic ship handling
Only intact hydrostatic control considerations are important for submarines, because (most) submarines cannot withstand any flooding larger than the pumping capacity of the bilge system and the reserve buoyancy is (mostly) not sufficient to compensate the weight of a flooded compartment. The intact hydrostatic control can be divided into: neutral buoyancy and trim capability, transverse metacentric height and reserve of buoyancy.

Neutral buoyancy and trim
The neutral buoyancy and trim capability is defined as achieving exact equality of the resultant buoyancy and weight forces. If the weight exceeds buoyancy the vessel will drop, this situation is known as 'negative buoyancy', if on the other hand the buoyancy exceeds the weight the vessel will rise, this is known as 'positive buoyancy'. The main causes for variations in displacement of the vessel are due to variation of seawater density and difference between compressibility of primary structure and seawater. The main causes for variations in mass of the vessel are due to consumption of consumable components and (dis-) charging seawater from (compensation) tanks.

Changes in the longitudinal balance are corrected by a variable mass system. A typical example of such system is the trim- and compensation system, which uses seawater as variable mass. The envelope of variation in weight and longitudinal moment, which can be obtained by such system, is represented by the equilibrium polygon, see figure 3.4. Starting with no mass in the system, the polygon represents the effect of subtracting or adding mass and moment respectively from or to the system. The origin of the polygon represents the starting point with all masses subtracted. The first side of the polygon in the first quadrant shows the effect of adding mass at the most forward location of the system. The slope of this side is determined by the longitudinal location and the length of this side is determined by the quantity of added mass. Subsequent masses are added working from forward to aft, until finally mass is added at the aftmost location of the system. Thus far, the polygon defines the maximum weight change which can be achieved by the variable mass system. The next part of the polygon represents the subtraction of masses, starting with the most forward mass and ending with the most aft mass.
Figure 3.4  Equilibrium polygon

Using this polygon, different loading conditions can be plotted. At least two extremes: full and light load have to be examined. Full condition might occur at departure from base, while light condition might occur at arrival. During an operation the water density can change. For each loading condition and water density the polygon shows the difference between displacement and mass and the difference between the longitudinal moment of gravity and buoyancy. If the centre of gravity of the boat is aft of the centre of buoyancy, then the resulting moment is defined by a positive value in the equilibrium polygon. The trim and compensating function can be most efficiently performed if the equilibrium polygon just encloses the extreme equilibrium points, thereby avoiding unnecessarily large variable ballast system.

Transverse meta centric height
The transverse meta centric height is defined as the distance between centre of gravity and meta centre. The meta centric height, corrected for free surface of tankage, is a measure for the righting moment when the submarine experiences an angle of heel or pitch. Three different situations can be distinguished: submerged, transit and surfaced.

When a submarine is in submerged condition the centre of buoyancy of the submarine has become stationary for any inclination. In other words; the vertical through the centre of buoyancy in the neutral position will intersect the vertical through the centre of buoyancy at any heel or pitch angle. The centre of buoyancy coincides the transverse and longitudinal meta centre, and the meta centric height is equal to the distance between the centre of gravity and centre of buoyancy (BG value). The BG value determines both the heel and pitch angles.
A small BG value causes on one hand large roll angles due to submerged heeling moments and on the other hand a small value for motion stability in vertical plane. A typical example of a submerged heeling moment is a ‘snap moment’, occurring when the submarine, having one appendage at the top of the outer hull, changes course.
A high BG value results in large motion stability, but can cause depth-control problems at low speeds, when the lifting forces of the hydroplanes can be inadequate to produce a sufficient large moment for diving and rising.
When the submarine goes from surfaced to submerged condition or vice versa, the so-called transition condition, the water plane area becomes zero while diving and becomes a positive value while surfacing. Therefore, while rising to the surfaced condition, the transverse second moment of water plane area becomes larger than zero, moving the meta centre upwards. However this meta centric height must be corrected for free surface effects, especially the effects due to partly filled tanks and delayed draining of free flooded spaces above the water plane. The delay in draining the free flooded spaces also causes a temporary raising of the centre of gravity. It is therefore necessary to ensure that during surfacing the centre of gravity does not migrate above the meta centre.

When the submarine is in surfaced condition the main ballast system has lost mass. As a consequence of the added mass approach the transverse second moment of area of the water plane remains constant. Only when the ballast tanks are partly filled, a correction for free flooded area must be made. If the volume of displacement is part of a body of revolution, then the water plane area remains constant for all heel inclinations. This constant meta centre, without correction for free surface effects of fluids in tanks, leads to positive righting arm curves until a heel-angle of 180°, with a maximum at an angle of 90°. Hence a lower meta centric height can be accepted when compared to surface ships with a similar displacement.

Reserve of buoyancy
The reserve of buoyancy of an intact submarine is defined as the ratio between the weight of the blowable Main Ballast Tank water and the weight of the boat in surfaced condition. For surfaced submarines this ratio expresses an ability to ride safely in rough seas. For submerged submarines it is sometimes more practical to express the weight of the blowable Main Ballast Tank water as ratio of the submerged displacement. This ratio is defined as the reserve of weight and expresses the ability to reach the surface in case of a flooding. The amount and position of the Main Ballast Tanks determine how much leak water can flood into the boat before it becomes impossible to re-surface.

In the surfaced condition the Main Ballast Tanks are empty, the longitudinal centre of the volume (LCV) of these tanks must be equal to LCV of the volume of displacement raised above the waterline. Otherwise the submarine will have a trim in surfaced condition while it has none in submerged condition.

Dynamic ship handling
The dynamic ship control performance parameters can be divided into dynamic stability and dynamic control manoeuvring characteristics in horizontal and vertical plane. The dynamic stability characteristics are defined as the response to small disturbances on course or depth with absence of actions of control components. Various kinds of motion stability are defined in ascending order: straight line stability, directional stability and positional stability, see figure 3.5 Therefore, a submarine that possesses positional stability must also possess both directional and straight line stability. If one
or more of these kinds of dynamic stability can not be achieved with fixed control components. they must be achieved with control actions operated either manually or automatically. However, using control component actions for dynamic stability is not desirable.

Figure 3.5  Straight line stability, directional stability and positional stability

The *dynamic control manoeuvring characteristics* are defined as the response to actions of control components on speed, course or depth. An example of the responses in the horizontal plane is the acceleration capability, tactical diameter of a turning circle at a certain speed, and in the vertical plane the ascent and descent acceleration at certain forward speeds. The acceleration capabilities are defined as ‘the time required to accelerate or decelerate the boat from a specified speed to another’.

The speed capability is defined as a minimum and maximum speed in both submerged and snorking condition. The minimum and maximum forward speed is limited due to possible incidents like: control system failure causing hydroplane jam, collision with surface ships or flooding. These restrictions are presented in a *safety envelope* [Burcher, 1994], which shows an unrestricted manoeuvring envelope in vertical plane, see figure 3.6.

Figure 3.6  Submarine safety envelope

The maximum speed is also limited by maximum torque and/or power, in other words limited by respectively a mechanical constraint or an overheating constraint. *Maximum continuous speed* defines the maximum speed where no overheating and mechanical overload occurs. *Burst speed* defines the maximum speed where no mechanical
overload occurs. However, burst speed can only be maintained for a limited period as overheating occurs.

### 3.4.3 Energy supply
The most important performance parameters of the components fulfilling the energy supply function are related to the energy-autonomy of the submarine. The **energy-autonomy** is defined as the ability to operate autonomous during the total mission endurance, without refill of any kind of energy. Performance parameters describing the energy-autonomy is the capability to deliver a defined amount of energy during the mission in both submerged and snorting condition. Usually a certain reserve amount of energy is required at the end of the mission.

The total time spent during the mission is called **total endurance.** Given the mean boat speed of advance, the total distance travelled during the mission is known, this distance is called **total range.** The **boat speed of advance** is defined as the weighted submerged and snorting speed. The weight factors are the percentages of respectively total submerged and snorting time relative to the mission time at which the submerged and snorting speed is maintained.

In submerged condition the endurance of submarines is limited to the amount of air independent energy supply. For example, diesel-electric submarines spend a percentage of the total mission time on recharging the batteries by snorting, this percentage is called **effective snorting rate.** If the time between the end of submerged condition and first moment of charging is included in the recharging time, then the percentage is called **indiscretion rate.** If recharging of the batteries is done with another air independent energy supplier, then the recharging time can be defined as a percentage of the total submerged time, this percentage is called **recovery rate** [Prins, 1988]. Both indiscretion- and recovery rate are dependent on the available charging power and required supply of energy during charging and discharging.

### 3.4.4 Ship management
The most important performance parameter of the components fulfilling the ship management function is the operational availability of the ship and crew. The **operational availability** is defined as the ratio between the time the ship and crew is available to fulfill its function and the total mission time.

The availability of a system can be increased by adding a second system with equal performance. The system becomes fully redundant when one of both system operates in stand-by mode, while the other system's (non-) failure is continually monitored.

### 3.4.5 Navigation and observation
The most important performance parameter of the components fulfilling the navigation and observation function is the detection sensitivity of the actual position, depth, course and speed of the submarine itself and of other submarines and ships.

For example, the sonar detection sensitivity can be measured by the ability to detect a noise source at a defined range, frequency, beam width and amount of self-noise due to hydrodynamic forces and mechanical vibrations.

### 3.4.6 Communication
The most important performance parameter of the components fulfilling the communication
function is the receiving sensitivity of radio waves and transmitting capability in both snorking and submerged condition.

3.4.7 Life support
The most important performance parameters of the components fulfilling the life support function are related to the life-autonomy of the submarine. The life-autonomy is defined as the ability to operate with a defined number of crew-members autonomously during the total mission endurance, without refill of any kind of provisions.

3.4.8 Special functions
The most important performance parameters of the components fulfilling the special functions are the ability to handle and control a defined number and type of mission systems. For a military submarine the performance is defined by, for example, its ability to communicate, detect threats and engage targets. A communication performance characteristic is, for example, the ability to communicate up to a specified speed and diving depth. Threat detection performance characteristics are, for example, the coverage and accuracy of range, depth. An engaging performance characteristic is, for example, the number of torpedoes which can be fired within a certain time period.
It goes without saying that fulfilling the special functions is the ultimate reason to bring the submarine to sea.

3.5 Conclusions
In literature, a lot of knowledge about submarine design is found. This knowledge can be structured according to three design sub-processes: sizing, balancing and performance calculations.
The first sub-process involves sizing of components, which are needed for fulfilling one or more functions required for a boat to perform a mission. Starting with eight main functions, all the sub-functions can be specified. Applying existing terminology is practical, as it supports the completeness of the defined functions and it corresponds to existing demarcations. For each function typical examples of currently applied components can be presented.
The second sub-process involves balancing the space, weight, energy, manning and cost of the boat. The space and weight of the boat must be balanced simultaneously, but can either be space driven or weight driven.
The last sub-process involves performance calculations, which determine the extent in which functions are fulfilled.
4

PROBLEM INTERPRETATION

The scientist explores what exists; the engineer creates what isn’t
Th. von Karman

This chapter discusses the problem interpretation process, which defines the design questions in the submarine design and their interrelations. The problem interpretation process expresses what it means to achieve an answer and in what context this answer can be used.

4.1 Submarine problem interpretation

Submarine conceptual design problems are characterised by exploratory design questions. The questions are called exploratory, as a single pass through the design process is not sufficient to produce an acceptable answer. The result requires adjustment of the problem formulations during the design process. As a result, both the problem and the solution co-evolve.

Design questions can be asked at different problem levels. The top-level problem for the submarine design process is defined by the question: ‘achieve an (optimal) design description of a boat which can fulfill a defined mission’. The word ‘optimal’ is between brackets as the question: ‘select the best design’ can only be answered by the designer. By incrementally modifying a design solution, the designer explores the possible solutions.

The top-level problem can be divided into sub-problems which are part of this problem, and sub-problems which are reversed. In reversed problems, the answer and the input for the question in the problem are exchanged. To give an example of the manner in which problems are reversed, consider the design question: ‘which improvements are possible when the conventional lead-acid batteries are replaced by an innovative type
of lower density batteries’. Replacing the batteries in the design cause a decrease of the total mass in the boat. The mass difference can, for example, be used for improving the diving depth. The new maximum diving depth in this sub-problem can be determined by reversing the ‘normal’ calculation method which determines the mass of the primary structure for a known maximum diving depth.

4.2 The top-level problem

Solving the top-level problem of the conceptual submarine design involves sizing, balancing and evaluating the performance of the boat as a whole, as explained in chapter three. Figure 4.1 shows the three sub-processes and two major decision points: the first point after the balancing process and the second point after the performance calculations. The first decision point checks the viability of the five balances: space, weight, energy, manning and cost balance. The second decision point checks the performance characteristics in relation to the mission specifications. When a decision is negative, the components of the boat must be resized.

![Flowchart for submarine design problem(s)](image)

The main problem within the sizing process is to determine the property values of the components from which the boat is assembled. Chapter three introduced the terms ‘supply’ and ‘consumption’ for properties while discussing the budget control. Table 4.1 contains the definitions of these terms, as applied for each property. The property values must be determined for each component or group of components.

<table>
<thead>
<tr>
<th>Property</th>
<th>Specified as...</th>
<th>‘Supply’</th>
<th>‘Consumption’</th>
</tr>
</thead>
<tbody>
<tr>
<td>space</td>
<td>Volume, deck area, deck height, deck width, and deck length.</td>
<td>creation</td>
<td>occupation</td>
</tr>
<tr>
<td>weight</td>
<td>Mass, displacement and their centroids.</td>
<td>buoyancy</td>
<td>weight</td>
</tr>
<tr>
<td>energy</td>
<td>Electric-, hydraulic, pneumatic- and heat energy</td>
<td>supply</td>
<td>energy load</td>
</tr>
<tr>
<td>manning</td>
<td>number of man hours per watch-period for operation and maintenance</td>
<td>facility</td>
<td>working load</td>
</tr>
<tr>
<td>capital</td>
<td>life-cycle cost, these include installation cost, material or component cost, operating cost, maintenance cost, and decommission cost.</td>
<td>budget</td>
<td>cost</td>
</tr>
</tbody>
</table>

42
The main problem within the balancing process is to achieve a viable balance between the component property values at the ‘supply’ side and at the ‘consumption’ side for each balance. The property values at the ‘supply’ side adds a value to a balance and property values at the ‘consumption’ side subtracts a value. If the balance is not viable, then one or more components have to be resized and/or re-located.

The main problem within the performance calculation process is to determine the submarines’ performance characteristics and compare them to the mission requirements. If the performance characteristics meet the mission requirements then a design solution is found, otherwise one or more components have to be resized and/or re-located.

Note, that both the cost and manning properties are not further discussed in this thesis, due to restricted research resources and lack of available data.

4.3 Submarine sizing problem

The sizing problem can be divided into two sub-problems which must be solved to determine the property values of the components from which the boat is assembled. The sub-problems concern: demarcation of components or groups of components and determination of the budgets for ‘supply’ and/or ‘consumption’ of the defined (groups of) components.

4.3.1 Demarcation of components

The first sub-problem in the sizing process concerns the demarcation of components. Chapter three introduced a decomposition of the submarine using terminology of an existing decomposition method. However, it is also mentioned that no standardised approach for the decomposition exists. Each decomposition is valid when it fulfills the criterion that the design of the whole is the sum of the components corresponding to the defined functions. Thus, no overlap or neglect is allowed.

Using an existing decomposition method introduces hundreds of components. Sizing this amount of components is not efficient for conceptual design. The components should be clustered to so-called objects. Figure 4.2 shows the decomposition and the clustering process. The objects are models predicting the properties of clustered groups of components. Using this definition of objects, clustering is dependent on each specific property. In this research the clustering is chosen the same for all properties, as this enables easy addition, alteration and removal of objects.

![Figure 4.2 Functional decomposition](image)
Changes in a collection must be made when the scope and/or precision and/or level of detail is not correct for the current design problem. The *scope* of the object collection refers to the component descriptions, which must be such that the top-level design problem can be solved. The *level of detail* refers to the quantity of individual described components within each object. Improving the scope and/or precision and/or level of detail indicates a better description of the submarine; however, it also means that more knowledge is needed during the design process. The *level of precision* of the object collection refers to the degree of accuracy when predicting the properties of objects.

4.3.2 Determination of budgets

The second problem in the sizing process is to determine the amount of supply and consumption of the individual properties for each object. The next sections contain the problems for sizing space, weight and energy properties.

**Sizing space**

Space sizing involves the determination of the space properties of objects which can become part of the in- and/or outboard part of the submarine. The demarcation of in- and outboard is defined by the primary boundary. Inboard space is located within the primary boundary, outboard space is located outside the primary boundary but within the outboard secondary boundary. For each object the intended location should be defined. Most objects are defined as exclusive inboard or exclusive outboard objects.

*Space consumption*

As mentioned in the space balance discussion in chapter three, the required space in a submarine is not only determined by volume but also by deck area, length, width, and height. The shape of the object determines the values for its required length, width, height, area and volume. The required object space is not necessarily box shaped due to the circular cross section of the pressure hull. Therefore, the required space dimensions are not necessarily equal to the (extreme) physical dimensions of the object. In other words, the volume of a component is not necessarily area times height, or its area is not necessarily width times length. Figure 4.3 shows an example of an object, with its space dimensions.

![Figure 4.3 Examples of cross sections of objects (shaft, main electric motor, diesel generator)](image)
The consumption of the space properties area and volume is determined by the object
envelopes. An object envelope is the space required for allocating a group of
components which defines an object. This envelope must be calculated for each object
and incorporates the total amount of exclusive space and weight required for its
components to function correctly.
For example, space is included for foundations and transportability requirements.
Typically, object envelopes include limitations on their sizes due to transportability
requirements through hatch openings. This requirement should only be applied for
components requiring major onshore overhauls like shaft-seal, coolers, converters,
main-switches, pumps, electric motors and/or battery cells.

The space properties length, width and height are consumed by object ergonomic
envelopes. The Ergonomic envelope contains the object box plus an additional space
used for access for production, operation and service of the components. This additional
space around the object box is called service space. As most objects require service
space, (parts of) these service spaces of two or more objects may overlap. For this
reason, service space include additional length, width and/or height requirements, but
not additional area and volume requirements. In this manner, the area and volume,
which is not occupied by components, represent the available area and volume for
service space.

Space supply
The problem of sizing the available space is to determine the physical dimensions of
the spaces within and outside the primary boundary. This problem can be divided into
a subdivision and sizing problem. The first problem determines the location of the
spaces and the second determines the size of the space which can fulfill all space
requirements of the objects which are allocated to that space.

The following example demonstrates the problem of sizing available space, which can
be observed during a design process. During the design of underwater vehicles, various
design alternatives (concepts) are examined in an attempt to optimise the use of the
available space. The top of Figure 4.4 shows the layout of the initial submarine design
and the bottom figure shows the layout of the same submarine at the end of the project
definition phase. Note that the layout within the primary structure has changed
considerably. Changes have been made in the arrangement of spaces and in the location
of components. These changes were made to correct the centre of gravity, which was
initially located too far to the aft to enable a weight balanced boat. This example shows
the main problem within the inboard space sizing problem: the design of a valid layout.
The submarine design might become puzzling as the available inboard space has a
circular cross section and most of the objects have box-shaped cross sections. To
generate a valid layout, often the location of spaces and/or components must change.
However, these changes should have been restricted to conceptual design since these
kind of changes are very time consuming and costly in the more advanced stages of the
design.
Sizing weight
Weight sizing involves the determination of the weight properties of objects which can become part of the submarine. The weight properties include the mass, volume of displacement and their centroid(s). Centroids are defined as centre of gravity and buoyancy relative to a co-ordinate system.

Weight consumption
The weight consumption of objects is a term for the amount of mass and the associated position of centre of gravity. For each object the mass and the centre of gravity relative to a local co-ordinate system must be determined. After allocating the object to a space, its global centre of gravity must be calculated.

Weight supply
The weight supply of objects is a term for the creation of volume of displacement and the associated position of centre of buoyancy. As the primary boundary is water-tight, the volume of displacement of the inboard part of the boat is determined by the volume of the primary boundary. The volume of displacement of the outboard part of the boat is determined by objects allocated to the outboard space. For each object the volume of displacement and the centre of buoyancy relative to a local co-ordinate system must be determined. After allocating the object to a space, its global centre of buoyancy must be calculated.

Sizing energy
The energy sizing problem includes the determination of the nominal energy consumption and supply budgets for each kind of energy. The nominal energy consumption for each type of energy is defined as the maximum energy consumption in any operating condition of the boat. The types of energy include: Direct Current, Alternating Current, Hydraulic, Pneumatic and Heat release energy.
Energy consumption

For each allocated object the energy consumption must be determined for each type of energy and for specified condition(s). The nominal energy consumption for each type of energy is calculated as the maximum energy consumption in any of the specified operating condition of the boat. To take into account uncertainties in the prediction of these consumptions, each nominal energy consumption is multiplied by a Marine Safety Factor. This factor defines the ratio between the design- and the nominal energy consumption for each kind of energy.

Energy supply

All energy is supplied by the objects fulfilling the energy supply function. Initially, in conventional diesel-electric submarines, all energy onboard is Direct Current energy stored in the batteries. Other types of energy are generated by transforming the DC energy. For each type of energy the maximum supply is determined by the maximum amount of energy which can be transformed by the objects.

4.4 Submarine balancing problems

The balancing problem must be solved to check the balance between the ‘supply’ and ‘consumption’ of the component properties. Initially, it is assumed that the weight balance is not considered to be a problem, which implies that the design is initially volume driven, as explained in chapter three. Of course, after solving the space balance problem, the weight and energy balances have to be solved as well.

4.4.1 Space balancing

The problem of achieving the space balance is to ensure that the available space is equal or larger than the required space in the boat. Like the space sizing problem, the space balance is divided into an in- and outboard space balance. For sizing the inboard space, the length of each space is chosen as the degree of freedom. Thus, the main problem of inboard balancing is to obtain this length, which must create sufficient space for accommodating the allocated objects.

4.4.2 Weight balancing

The problem of achieving the weight balance is to check the neutral buoyancy of the boat (while submerged). This check includes first that the amount of the total weight equals the amount of the total displacement for a defined seawater density, and second that the centroid of the weight is at sufficient distance straight below the centroid of displacement.

4.4.3 Energy balancing

The problem of achieving the energy balance is to check the viability of the balance. The viability of the energy balance is shown when the amount of required Direct Current, Alternating Current, Hydraulic, Pneumatic and Heat release energy for any defined operating condition can be supplied.
4.5 Performance prediction problems

The performance prediction problem can be divided into two sub-problems which must be solved to check the performance characteristics in relation to the mission specifications. The sub-problems concern: calculation of performance characteristics and comparing achieved performance to mission specification.

4.5.1 Calculation of performance characteristics
The first sub-problem in the performance calculation process concerns assessing the relevant performance characteristics with respect to the required scope, precision and level of detail. The scope of the performance refers to the mission requirements which are considered relevant to the design problem. The level of detail defines the level of aggregation which must be adequate for the problem solving activities, this level must neither be too generic nor too detailed. The precision of the performance list refers to the degree of accuracy of the prediction.

The following example illustrates the defined words 'scope', 'precision' and 'level of detail' in respect to the performance characteristics.

A typical performance calculation is the burst time calculation. The scope of this calculation is to determine the maximum duration during which the burst speed in submerged condition can be maintained. For an attack mission the burst time is vital, as it determines the maximum area in which the submarine can hide after an attack. The level of detail refers to the sub-problems which must be solved. The burst time calculation includes the prediction of two endurances: the time until the Main Electric Motor becomes overheated and the time until the battery capacity is exhausted in burst condition. The shortest of these endurances determines the burst time. The level of precision of this performance calculation refers to the accuracy of the prediction. To calculate the burst time accurately the calculation includes e.g. effect of initial winding temperature and increasing battery resistance during fast and deep discharge. Important parameters influencing the burst time are e.g. the temperature class of the armature windings’ insulation and the discharge range of the batteries.

4.5.2 Comparing achieved performance to mission specifications
The comparison problem concerns the difference between the achieved performance and the required performance. For each performance characteristic the scope, precision and level of detail determine whether a difference can be accepted or not. Consequently, a definition of an acceptable difference cannot be provided in general.

4.6 Implications for this research

Submarine conceptual design problems are characterised by exploratory design questions, which means that both the answers and the questions evolve during the
design process. This exploratory nature of the submarine design process is found at all levels of problem definition, starting at the top-level. The top-level problem for the submarine design process is defined by the question: 'achieve a design description of a boat which can fulfill a defined mission'. Dividing this problem into a number of sub-problems according to the three design sub-processes: sizing, balancing and performance calculations, showed an efficient way of structuring the relevant problems. The sub-problems provide control to the knowledge acquisition process as described in the next chapters.
5

KNOWLEDGE ACQUISITION METHODS

5.1 Submarine knowledge acquisition methods

The design models describe what knowledge is used within the submarine design process. These models give an overview of the acquired design knowledge at various levels of detail. The acquisition for design models includes searching and structuring of knowledge used by the designers in executing their tasks. In recent literature several books are available on the subject of this task [Waldron, 1992] [Durkin, 1994] [Guida, 1994] [Miles, 1994]. This literature provides a survey of most commonly used acquisition techniques in knowledge transfer. All these techniques generally have the same three steps: collecting data, analysing and coding. One should realise that most knowledge
is not acquired from scratch, but is built on information extracted from previous acquisitions. Each of the three steps is discussed in the following sub-paragraphs.

5.1.1 Data collection
The data collection finds sources of data that provides knowledge for performing the different design tasks. The available sources of data can be classified by the type of knowledge: deep and shallow knowledge [Märk, 1992]. Deep knowledge contains knowledge based on first principles embodied in physics. Well known examples of deep knowledge are Archimedes' principle, Maxwell's law, or Hopkinson's coefficient. Shallow knowledge contains heuristic knowledge generated from the experience of solving past problems. Well known examples of shallow knowledge are so-called regression models based on empirical data. Table 5.1 provides a list of different data acquisition sources and relevant knowledge types. Each source is briefly reviewed.

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Knowledge Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search in open literature</td>
<td>Deep and Shallow</td>
</tr>
<tr>
<td>Interview between expert and knowledge engineer</td>
<td>Deep and Shallow</td>
</tr>
<tr>
<td>Extracting knowledge from existing design programs</td>
<td>Deep and Shallow</td>
</tr>
<tr>
<td>Study the history of previous designs</td>
<td>Shallow</td>
</tr>
<tr>
<td>Design standards, guidelines</td>
<td>Shallow</td>
</tr>
</tbody>
</table>

**Literature search** includes finding all sources of data in the form of documents, such as books, reports, regulations. These documents not only provide insight into the deep and shallow knowledge, but also clarifies the terminology as applied in submarine design.

**Interview** between expert and knowledge engineer can be performed in many different ways. Guide [1994] presents a list of basic techniques which can be applied to single or multiple experts. The most promising technique for gathering design data is called 'paper review'. The knowledge engineer prepares the (intermediate) results of the data analysis and modelling activity into a paper, which is submitted to the experts. By collecting feedback from the (different) experts, the data can be refined and verified. This process can be repeated several times until the results are satisfactory.

**Existing design programs** contain structured amounts of existing data for performing specific tasks. By using the source-code in text format relevant design data can be extracted.

**History of previous designs** contains data that can be divided into specific and general data. Specific data contain records about properties of components which are used in
specific (existing) designs. A typical example of such components is the accommodation of a submarine. However, only a small number of existing submarine designs have been made in the world, therefore this data source contains only a small body of data. This body of data becomes even smaller when only the sources in the Netherlands are considered. Further more, some parts of this data cannot be used in this thesis for sensitivity, or classification reasons.

General data contain records about properties of components which are designed and developed separately from the submarine design. Examples of such components are: diesel engines, batteries, or main electric motor. These data records can be extended, with records containing the properties of new components, e.g. air independent diesel engine or fuel cells.

Design standards represent codified historical experience.

5.1.2 Analysing data
The analysis task identifies the collected data, involving interpretation of data and formulation of documented design knowledge. This knowledge is represented by means of written natural language, formulae, values, tables or diagrams and also includes the information needed to understand why a specific collection of data is identified. Design knowledge predicts limited abstractions of particular phenomena. Therefore the choices leading to a required scope, precision and level of detail have to be documented.

A promising starting point for identifying design data is to start with an investigation of models based on deep or shallow knowledge employed in the design. Where existing design models fail to answer design questions at an adequate scope, precision and level of detail, the demand for replacement or refinement is initiated.

The kind of available data about a design gives a clue for the kind of modelling that can be done for a certain task. The data can be divided into two sets: those that display a particular interpretation of the design or a more general interpretation. The first set of data generates design models using a set of previous design cases. These cases are candidate solutions for given specifications. The design model must support the selection of a case from the collection of cases. A typical example of these models is the selection of a manufacturer and type of diesel engine from a database of existing diesel engines.

The second set of data generates adaptable design models. Generating adaptable models start with a specification of the problem. Successive refinement through decomposition of problems constructs the knowledge base of design models. Refinement proceeds until the required scope, precision and level of detail is achieved. In general this way of modelling uses both deep and shallow knowledge. A typical example of these models is the Main Electric Motor sizing model [Pel, 1995], which uses deep knowledge (such as Lorentz principle), and shallow knowledge (such as the ratio between length of the winding head and length of the pole pitch) to determine the size of a direct current electric motor for a specified output power and rotation rate. Analysing existing adaptable models, the following observation can be made: increasing the ratio between
deep and shallow knowledge in the design models increases the capability of the model to diverge from conventional modes of thinking. The knowledge engineer should therefore try to develop design models that explicitly explains the heuristics of the expert in terms of deep knowledge. However, if this is not possible the knowledge engineer should remember Sussman’s statement:

"It is better to have a naive model of a sophisticated theory, than to have a sophisticated model of a naive theory"

In this statement ‘Naive’ refers to incomplete, intuitive, not scientifically rigid and ‘Sophisticated’ refers to complete, formal, scientifically well-founded.

In order to judge how well a design model achieves its purpose the following aspects should be considered: flexibility, validity, responsiveness, sensitivity and consistency. Table 5.2 explains these aspects.

<table>
<thead>
<tr>
<th>Table 5.2</th>
<th>Check on design models</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Check</strong></td>
<td><strong>Quantifies</strong></td>
</tr>
<tr>
<td>Flexibility</td>
<td>the problems for which the model can be applied</td>
</tr>
<tr>
<td>Validity</td>
<td>a valid value range of input data, correctness of results</td>
</tr>
<tr>
<td>Responsiveness</td>
<td>the ability for the user to interact with the model</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>the variation in the results according to the variation in the initial situation</td>
</tr>
<tr>
<td>Consistency</td>
<td>the degree of prevention of logical conflicts</td>
</tr>
</tbody>
</table>

5.1.3 Coding the design knowledge

The knowledge coding task involves the development of design algorithms into a defined format. This format can be: numerical, geometric and topological knowledge. Each format uses a special jargon, having a meaning both to the designer and to the tool. The expert has to check the coded knowledge that both the designer and the tool interpret the acquired knowledge in the same manner.

Coding numerical knowledge

The *numerical knowledge* is codified by parameters and relationships between these parameters in terms of mathematical and/or conditional expressions.

*Mathematical parameters* describe numerical facts about the design. Important characteristics of parameters are their discriminative and manipulative abilities. Parameters with high discriminative and manipulative abilities must be codified transparently to the designer. A *discriminative ability* expresses the influence of a parameter value change on the performance of the design. The *manipulative ability* expresses the degree of freedom for changing a parameter value. Parameters can be
divided into two main groups: design parameters with a high manipulative ability and constant value parameters with a low ability. The value of a design parameter is either determined by one or a set of mathematical expressions, or must be provided by the designer. The value of a constant cannot be influenced, typical examples of parameters with a low manipulative ability are physical properties or predictors in regression models [Sen, 1990].

**Mathematical relationships** describe the dependency between the parameters. Using this definition, the ‘=’ sign in mathematics codifies a dependency among the design parameters. This definition is important as a dependency defines a direction in the relationship, which can either be valid in one direction or in both directions.

Frequently more than one alternative (empirically or physically based) relationship exist for predicting a design characteristic. When comparing these alternatives, the following statement is followed [MacCallum, 1990]: "It is in the nature of the design process that increasing accuracy (for predicting a design characteristic) can be modelled with increasing availability of detail (read: ‘parameters with high discriminative and manipulative abilities’)."

The designer should however be aware that this statement is only valid when the design problem requires examining the influence of those design parameters which are not included in the models with less detail. Motivated by the above given statement, the codification of mathematical models starts with a selection of relevant design parameters. Which design parameters are relevant and which are not, depends on the design problem at hand. For example, when calculating the submerged endurance at hoovering speed the propulsion power can almost be neglected compared to the required hotel load while at burst speed the opposite effect occurs.

**Conditional expressions** describe the conditions and ranges of validity beyond which the model is not valid. Specifically, relationships based on empirical knowledge, have a limited validity, dependent on the context in which the relationship is derived. But also the selection or inter- and extrapolations from a table of values can be limited by conditional expressions.

**Coding geometric knowledge**
The **geometrical knowledge** is codified by the size and shape of the space required for or provided by components in the boat. The geometrical knowledge about the required space is defined by the object properties: height, length, width, area and volume. The geometrical knowledge about the available space is defined by the properties of the space boundaries. Figure 5.1 shows examples of the object properties. Note that the required height for the console is smaller than the overall height. Typically, the shape of a console is different for each submarine and depends on the size and shape of the available space. The correct volume and area requirements must ensure that sufficient space is available above the deck area to which the console is allocated.
Figure 5.1 Transverse and longitudinal cross section of control centre in a pressure hull

Coding topological knowledge
The topological knowledge is codified by the relative location of components from which a unique design is assembled. This knowledge expresses the characteristics of the spatial layout or also called arrangement. The spatial layout contains the spatial layout of spaces and the spatial layout of components. In literature several methods can be found for codifying the topological knowledge.

Coding spatial layout of spaces
In literature two different methods are presented for defining the spatial layout of spaces: the first method proceeds from structural elements to spaces, and the other method proceeds the reverse way. The structural elements are the boundaries of the spaces, which can either be made from real materials or from nothing. The last type of boundary is called imaginary. Examples of structural elements in a ship are bulkheads and decks.

From structural elements to spaces starts with defining and sizing structural elements followed by the determination of enclosed spaces. This method is analogous to the representation of graphical objects by surface boundaries as used in computer graphics [Foley, 1994]. Several references use this method in ship design [Cort, 1987][Hills, 1989][Lee, 1991][Laansma, 1992]. These references show two main advantages of the method: structural elements can be defined at an arbitrary location, thereby generating every requested spatial layout, and each structural element can be given a meaning. However this method has also some drawbacks: changes in the layout can only be achieved by changes made at the structural element level, and moving a space to another location is impossible because only structural elements can be moved.

From spaces to structural elements starts with defining and sizing spaces followed by the determination of the structural elements. This method is analogous to the representation of graphical objects by volumetric solids as used in computer graphics [Foley, 1994]. The main advantages of this method are that the shape and size of the space can be defined with a limited amount of data, and changes in the spatial layout, like adding, moving or deleting, are relatively uncomplicated. The main limitation of this method is the required re-definition of the structural elements when spatial changes are made.

56
During conceptual design uncomplicated adding, moving or deleting of spaces supports the exploration of possible solutions more than uncomplicated adding, moving or deleting meaningful structural elements. Thus, the method from spaces to structural elements is more efficient for coding the topology of spaces. The hierarchy of available spaces is shown in figure 5.2. The hull at the top level is divided along its length (by bulkheads) into one or more compartments. At the second level each compartment is divided along its height (by decks) into one or more cells. At the lowest level each cell can be divided along its length (by separation walls) into one or more rooms.

![Figure 5.2 Definition of compartments, cells and structural elements for a surface ship](image)

*Figure 5.2 Definition of compartments, cells and structural elements for a surface ship*

**Coding spatial layout of components**

In literature two different methods are presented for defining the spatial layout of components: locating the components at a specific location or locating the components at a non-specific location.

Coding the locations of components at a specific location can be achieved by a drawing, a grid [Andre, 1986], or a nodal figure [Cort, 1987]. The location of each component can accurately be specified. However, the designer is confronted with specifying a large amount of topological information, often with an accuracy unsuitable to the conceptual stage of design.

Alternatively, the location of components can be given non-specifically. Coding topological knowledge about locating components non-specifically can be achieved by an allocation-sequence of components to a space. A limited amount of topological knowledge can be coded. For example topological knowledge such as adjacency or separation can not be represented. As a consequence, allocating objects non-specifically does not involve checking that a viable layout of objects within that space is achieved.

During conceptual design uncomplicated specification of the location of components supports the exploration of possible solutions more than accurately specifying the location of components. Thus, non-specific component allocation is more efficient for coding the topology of components. The allocation sequence of components is coded by a list of objects, in which the top represents the first and the bottom the last allocated components.
5.2 Conclusions

Design knowledge acquisition contains three tasks: data collection, analysing data and coding the design knowledge. Five sources of submarine design knowledge are distinguished: literature search, interviews, existing design programs, history of previous designs and design standards. An important source of information is the historical data of previous designs. Utilisation of this data source is limited, due to the few number of existing designs. To overcome this limitation, more general applicable knowledge sources should be used. If possible, deep knowledge should be used instead of shallow knowledge, as deep knowledge enables the designer to diverge from the conventional modes of thinking without affecting the correctness of the results. The deep and shallow knowledge should be codified into numerical, geometrical and/or topological forms.
THE SUBMARINE DESIGN MODEL

If design means anything, it must have a sense of human rightness
D.J. Andrews

This chapter discusses the application of various design models for predicting the size and performance of components and the boat as a whole. This chapter reviews the existing and newly developed knowledge about design models for sizing, balancing and calculating the performance of submarines. The importance of evaluating existing knowledge in the design process is illustrated by Weisberg's statement [Weisberg, 1986]:

"This might mean, perhaps paradoxically, that in order to produce something new, one should first become as knowledgeable as possible about the old"

The first paragraph of this chapter starts with an introduction to the submarine design knowledge, to determine the most relevant problem areas. The following paragraphs describe the acquired models. The level of detail is dependent on the level of novelty. For example, much attention is given to an uncommon space balancing model. The models are presented using the framework of eight main submarine functions as introduced in chapter three.

6.1 Submarine design models

To solve the problems which are specified in the previous paragraph, submarine design knowledge has to be acquired. This paragraph shows the current available knowledge for solving those problems. The first question which arises when acquiring knowledge is: ‘what is the required scope, precision and level of detail for the acquired knowledge to solve the top-level problem?’ The required precision and level of detail, for predicting the object properties is different for each defined object as well as for each
of its properties. High precision and level of detail is required for objects sizing and performance prediction, which ‘supply’ or ‘consume’ a significant part of the budget of a property.

For recognising the dominating objects, which ‘consume’ a significant part of the available internal volume, mass and electric energy of a submarine, several classes of diesel-electric submarines built in the 1980’s have been evaluated. A comparison study by Stenard [1988] presents percentages of internal volume and mass of components for submarines with submerged displacement between 1200 - 2900 [ton]. Table 6.1 shows mean values of four different classes of boats, which are examined in this study. The presented percentages can be used to give an indication of values which are achieved in practice. In general, this comparison study shows that the largest percentage of the internal volume is occupied by the components fulfilling the Manoeuvring and Energy supply function and considerably less by the Life support and other functions. The largest percentages of the standard displacement is occupied by the objects fulfilling the Carrying platform, Manoeuvring and Energy supply function.

Table 6.1 Summary of internal volume and mass comparison, by Stenard [1988]

<table>
<thead>
<tr>
<th></th>
<th>percentage of internal volume [%]</th>
<th>percentage of standard displacement [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrying platform</td>
<td></td>
<td>41</td>
</tr>
<tr>
<td>Manoeuvring Energy supply</td>
<td>55</td>
<td>46</td>
</tr>
<tr>
<td>Ship management</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Navigation &amp; Observation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Life support</td>
<td>22</td>
<td>5</td>
</tr>
<tr>
<td>Special functions</td>
<td>12</td>
<td>4</td>
</tr>
</tbody>
</table>

Note: standard displacement is equal to surfaced displacement minus variable loads

Individual classes of submarines can differ from these percentages due to extreme design requirements. Typical examples of these extremes are: relative large mass for carrying platform due to extreme diving depth requirement, or relative large volume and mass for Manoeuvring and Energy supply caused by an extreme submerged range at high speed requirement, or relative large volume for life support caused by extreme total mission endurance.

An evaluation study by Pel [1995] presents percentages of installed nominal load of electric energy consumers for submarines with submerged displacement around 2900 [ton]. Table 6.2 presents the results of this evaluation.

The presented percentages can be used to give an indication of values which are achieved in practice. In general, this evaluation study shows the largest percentage of the electric energy is consumed by the components fulfilling the Manoeuvring and Energy supply function and considerably less by other functions The percentages are

60
based on total nominal load of electric energy consumers in any type of the electric energy. Thus, the nominal loads are not converted to the Direct Current source type of energy. Percentages for burst speed and maximum continuous speed conditions are presented to show the increasing significance of propulsion on the budget when the required submerged speed increases. Both conditions are explained in more detail when discussing the performance prediction problem in paragraph 6.4.

<table>
<thead>
<tr>
<th>% Total nominal (electric) load</th>
<th>Including Propulsion load:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burst speed</td>
<td>Max. Continuous speed</td>
</tr>
<tr>
<td>Carrying platform</td>
<td>-</td>
</tr>
<tr>
<td>Maneuvering</td>
<td>86</td>
</tr>
<tr>
<td>Energy supply</td>
<td>9</td>
</tr>
<tr>
<td>Ship management</td>
<td>2</td>
</tr>
<tr>
<td>Navigation &amp; Observation</td>
<td></td>
</tr>
<tr>
<td>Communication</td>
<td></td>
</tr>
<tr>
<td>Life support</td>
<td>2</td>
</tr>
<tr>
<td>Special functions</td>
<td>1</td>
</tr>
</tbody>
</table>

From the above presented percentages can be concluded that the components, fulfilling the Maneuvering and Energy supply function, determine a significant part of the three budgets, relevant for this thesis. Further the components fulfilling the Carrying platform function are significant for the weight budget and the Life support function is significant for the volume budget. Appendix A contains a list of the objects fulfilling these functions.

Several detailed studies examine, as part of the SUBCEM project, each of these significant contributions to the different budgets. The following studies analyse the Maneuvering and Energy supply function: [De Leroi, 1993], [Sipkema, 1993], [Kuilenburg, 1994], [de Wit, 1994] [van Diermen, 1995], [Pel, 1995a,b], [van der Nat, 1996d] and [Wilgenhof, 1996], [Stapersma, 1998]. The Carrying platform function is analysed by Groen [1996] and van der Nat [1996c], and the Life support function is analysed by Claessen [1994].

The next paragraphs summarise a few of these studies to demonstrate how sources, assumptions and restrictions of the acquired knowledge are managed. Special attention is given to the representation of in- and output parameters with high discriminative ability, and dependency-direction when a relationship is valid in one direction. Appendices B and C present detailed results of two studies, one for a sizing study and one for a performance calculation study.
6.2 Models for sizing

The models for sizing the submarine are divided into models for predicting the space, weight and energy properties of objects, spaces and structural elements.

6.2.1 Models for object sizing

The problem of the object sizing is to determine budgets for weight, space and energy required for components to fulfill their functions. In chapter three the Ship Work Breakdown Structure (SWBS) [NavSea, 1985] at the fourth level is advised for identification of the components. This decomposition method is applied in the design process of existing submarine designs, giving (some) guarantee that no overlap or neglect occurs. To limit the amount of components, the following criteria are used to cluster the components to objects:

All components in an object are part of the same function description.
- All components in an object have the same type of space properties.
- All components in an object occupy a space which belong exclusively to these components. For example the space required for the component’s displacement due to shock is part of its exclusive space.

For conceptual design less than 100 objects should be sufficient for describing the total submarine.

First experiences show that about 50 objects are sufficient to describe the propulsion and energy supply function (engine rooms) of an existing 3000 [ton] submerged displacement submarine [Daniëls, 1996]. The engine rooms in this boat utilise more than half the total volume inside the boat. It is therefore expected that the total number of objects is less than 100. Appendix A contains an example of a collection of defined objects for submarine design. Detailed description of this collection is reported in [vd Nat, 1995b].

First the object space and weight sizing models are discussed, then the energy sizing models.

Models for object space and weight sizing

For each defined object a model for sizing the space and weight properties must be developed. The space properties include the volume, deck area, deck height, deck width and deck length required for allocating the object to the space. The weight properties include the mass, volume of displacement and their local centroids. If the object requires more structure for its foundation than provided by the deck, then the mass of this additional structure is part of the object mass.

Which space and weight properties have to be determined depend on the characteristics of the components described by the object. The space and weight characteristics are described by three different object types:
• Object type 1: height, length, width, area, volume, mass, x-centroid and z-centroid
• Object type 2: height, area, volume, mass, and z-centroid
• Object type 3: height, volume and mass

Which type is appropriate for an object depends on the components described and on its size and contour relative to the size and contour of the submarine. In general the first object type is applied for a few large components like Main Electric motor and Diesel Generators. The second object type is most commonly applied for inboard objects containing a number of smaller components. Typical type two objects are accommodation or auxiliary machinery. The third type is applied for inboard objects which can be allocated to any contour of the space in the boat, like tankage.

Measuring the object dimension at its extreme contour, will (sometimes) cause a conservative space allocation for the object. For example, the main electric motor has length, width and height requirements. Figure 6.1 shows the required length for the main electric motor room for different definitions of required space contours for the main electric motor.

Figure 6.1 Main Electric Motor: space definitions

To define the space requirements for an object, its type does not always give sufficient information. A number of space attributes are developed, specifying additional space or weight characteristics. Table 6.3 defines these attributes.

One or a combination of attributes can be defined for objects, for example Energy Distribution has a combination of Margin and FreeVolInc. The ‘Margin’ attribute is applied to this object because the components fulfilling the Energy Distribution function are connecting the objects allocated to a space. When the space dimensions grow, the connecting paths and therefore the space requirements of this object increase. The ‘FreeVolInc’ attribute is applied because most of the components of this object are located above or besides the objects to which they connect.
<table>
<thead>
<tr>
<th>Divided</th>
<th>The object can be divided into two or more parts, which can be located at different locations. Example: Batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill up</td>
<td>Fill up objects can only be defined for object type 2 and 3, the object size is dependent on the non-occupied area respectively volume. Example: Tanks.</td>
</tr>
<tr>
<td>FreeVolIncl</td>
<td>Free Volume Incl objects can only be defined for inboard object type 3, the object can be located above occupied area within the volume which is not occupied by prior allocated objects. Example: Diesel Engine Exhaust Gas system</td>
</tr>
<tr>
<td>VolBetwFramesIncl</td>
<td>The Volume Between Frames Incl objects volume can be located between frames of the pressure hull, deck or bulkhead structure. Outboard objects are always Volume Between Frames Incl. Example: Fuel Oil</td>
</tr>
<tr>
<td>Orientation</td>
<td>The orientation of a space is defined by the alignment of the component relative to the centre line of the boat. Orientation can only be defined for inboard object type 1, the length and width are exchanged as well as its x- and z-centroid. Example: Steering control console</td>
</tr>
<tr>
<td>Margin</td>
<td>Margin objects can only be defined for inboard object type 2 and 3, the object size is dependent on the occupied area respectively volume of prior allocated objects to the space. Example: Service space</td>
</tr>
<tr>
<td>MaxHeight</td>
<td>MaxHeight can only be defined for inboard-object type 1, the net-height of the object is equal to the maximum height in the space at the width of the object. Example: Inboard part of Periscopes</td>
</tr>
<tr>
<td>VariableWeight</td>
<td>Variable load objects are composed of components which weight vary during the mission. Examples: Provisions, Fuel Oil, WCT, MBT</td>
</tr>
</tbody>
</table>

The object properties are sized by algorithms involving different dependencies such as:

- Dependency on the size of other objects. For example the size of the propulsion transmission object depends on the size of the main electric motor (maximum torque), while the size of main electric motor depends on the size of the main batteries (maximum voltage).
- Dependency on a balance. For example the size of the AC-energy conversion objects depend on the maximum required AC-power, which is determined by the AC-energy balance.
- Dependency on the amount of support to other objects. For example the masts support the external communication sensors.
- Dependency on shape and size of space in the boat. For example tank structure depends on the size of the allocated tank fluids.

Dependencies on properties of already allocated objects, or performance of the boat should be avoided, as they are unknown during the sizing of the individual components. These dependencies cause implicit mathematical relationships, which also include the (computational time consuming) inboard sizing process. Solving implicit mathematical relationships involve solving (non-) linear relations simultaneously,
requiring an iterative method. As the inboard sizing process is computational time consuming, this reflects on the whole process. The following dependencies should be avoided:

- Object properties dependent on location of other objects. For example local energy distribution (E-cables) depends on the location of the main batteries, switch board, main electric motor and diesel generator sets.
- Object properties dependent on size of boat. For example margin ballast depends on mass and global centroids of the boat.
- Object properties depend on performance of the boat. For example the propeller is sized to achieve the highest possible burst speed.

If only the object weight properties rely on the above dependencies, then the object should initially be allocated to a space, whereas the correct weight properties are calculated after sizing the complete boat or calculating the performance.

*Object space and weight sizing example*

As an example of the object space and weight sizing models, a summary of the model for the inboard component(s) fulfilling the Propulsion driving function is presented here. According to chapter five, the summary of this model is viewed from the perspective of the scope, the level of detail, and precision of the knowledge.

A detailed description of this model is described by Deleroi [1994]. By making a distinction between burst and maximum continuous condition, Pel [1995a] further refined this model. The model and its refinements are specially developed for SUBCEM (see Appendix B).

*Scope Propulsion Driving model*

The scope of the knowledge refers to the purpose, the applied design requirements, and the limitations of the model. The *purpose of the sizing model* for the component(s) fulfilling the Propulsion driving function is defined as: calculate the required space and weight properties of a direct current Main Electric Motor (MEM).

The *design requirements* define the required performance for a specified condition. Two main conditions in the sizing algorithm for the MEM are distinguished; a so-called burst and maximum continuous condition. The brake power and associated rotation rate of the MEM in burst condition determines the maximum allowable mechanical and magnetic load, while the maximum allowable thermal load is exceeded. This condition can therefore only be sustained for a limited period. The maximum continuous condition determines the maximum allowable thermal load and can be thus be sustained for an unlimited period (see also paragraph 3.4).

The *design limitations* define the physical and technical limitations which cannot be exceeded when sizing. The most important limitations for the MEM are related to the magnetic- and electric- and mechanical loads. The magnetic load is limited by magnetic circuit saturation of the armature teeth, and the maximum effective iron length. The electric load is limited by the maximum armature current density, and the maximum
voltage between two commutator bars. The mechanical load is limited by the maximum allowable radial forces at the circumference of the rotor.

**Level of detail Propulsion Driving model**

The level of detail refers to the level of sub-division of the object into components. The level of sub-division for an object is determined by its design requirements and by its relationships with other objects.

The design requirements can be defined for more than one design condition. The distinction between different conditions requires that some components are designed according to one condition and others according to another. For the MEM the distinction between burst and maximum continuous conditions requires separate sizing of, on the one hand the mechanical loaded components like bearings and on the other hand, magnetic- and thermal loaded parts like (inter-) poles, stator yoke, or cooler.

An object has relationships with other objects. These relationships have consequences for some of the components within other objects. To predict the effects of these relationships on the components the level of detail has to be adequate. For the MEM typical relationships between objects can be defined such as: the size of commutator is related to the main battery by the maximum voltage and to the main-switches by the maximum current. Typical relationships in which the MEM defines a restriction to another object are the brake power and rotational speed which define the design condition for the propeller.

**Level of precision Propulsion Driving model**

The level of precision refers to the accuracy of the results. The accuracy is determined by the quality and quantity of the knowledge.

The quality of the knowledge is measured by the ability to predict the object properties for a wide range of performance values. In general, high quality requires a high ratio between deep and shallow knowledge. Sometimes more than one model can be acquired, each having a different ratio. Depending on the design problem one of these models can be chosen for predicting the properties. For example, for the MEM, two models have been developed for predicting its mass. A simple model, with low level quality, predicts the mass for MEMs with similar structural requirements compared to the series of existing MEM. A complex model, with high level quality, predicts the mass for MEMs having more specific structural requirements, such as number of armatures, or shock requirements.

The quantity of the knowledge is measured by the amount of parameters with high discriminative ability (parameter value which has large effect on outcome of model) and manipulative ability (parameter which should be adjustable). The value of parameters with a high discriminative and manipulative ability are essential inputs for the model and must be determined either directly by the designer or indirectly by other object models. Examples of these parameters in the MEM model are: the maximum current through an armature, the maximum voltage at the terminals, the burst- and maximum continuous brake power with their associated number of revolutions, and the number of armatures on one shaft. Parameters with a high discriminative ability but a low manipulative ability represent technical constants. These parameters are explicitly
defined in the model and always have a default value. Examples in the MEM model of these parameters are: armature winding factor, main airgap induction, or number of pole pairs. Parameters with low discriminative and manipulative ability represent empirical constants. These parameters are implicitly defined in the model by their values, an explanation of these values is given in the reference text of the model. Examples in the MEM model of these parameters are: brush friction coefficient, or pole shoe volume correction factor.

Appendix B contains a short description of the knowledge required to determine the dimensions of a Direct Current Main Electric Motor. Using this model, the parameter values with a high discriminative and manipulative ability are varied (see chapter eight).

Models for object energy sizing
The purpose of the energy sizing model is to determine the energy consumption of the objects. These include the nominal loads for the Direct Current (DC), Alternating Current (AC), Hydraulic, Pneumatic and Heat release. The load is defined as the maximum required load in any of the conditions defined in table 6.4 [Pel, 1995b].

<table>
<thead>
<tr>
<th>Condition</th>
<th>Definition of operating conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survival deep</td>
<td>Submerged condition in which all non-vital equipment is shut down</td>
</tr>
<tr>
<td>Patrol deep</td>
<td>Submerged condition in which no energy saving measures are taken</td>
</tr>
<tr>
<td>Full snorking</td>
<td>Snorking condition in which as many as possible tasks are performed</td>
</tr>
<tr>
<td>Patrol snorking</td>
<td>Snorking condition in which all tasks are performed to ensure safe re-charge of batteries and refreshment of air</td>
</tr>
</tbody>
</table>

The uncertainties in the accuracy of the prediction of the maximum load are expressed by a so-called marine safety factor, see chapter four.

As an example of these models a summary of the sizing model for the component(s) fulfilling the Energy Conversion function is presented here. The summary of the design knowledge is viewed from the perspective of scope, level of detail, and precision of the knowledge. Detailed description of this model is described by Pel [1995b] and van Diermen [1995].

Scope Energy Conversion model
The purpose of the sizing model for the component(s) fulfilling the Energy Conversion function is defined by: calculate the nominal loads for the energy conversion systems for each of the four relevant operational conditions. The energy formats are specified in table 6.5.
Table 6.5  Energy format definitions

<table>
<thead>
<tr>
<th>Energy format</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Battery Voltage, 24V</td>
<td>kW</td>
</tr>
<tr>
<td>AC 440V@60Hz, 115V @ 60 Hz, 115V @ 400Hz</td>
<td>kW</td>
</tr>
<tr>
<td>Hydraulic oil</td>
<td>litres per minute @ e.g. 130 bar</td>
</tr>
<tr>
<td>High pressure air</td>
<td>Normal m³ per hour</td>
</tr>
<tr>
<td>Chilled water, Conditioned air</td>
<td>kW</td>
</tr>
<tr>
<td>Sea cooling water, Fresh cooling water</td>
<td>m³ per hour @ ΔT</td>
</tr>
</tbody>
</table>

Level of detail Energy Conversion model

The required amount of energy is analysed for each object, defining for each condition an operational-, load- and simultaneity factor, see table 6.6. The total required amount of energy for the objects is calculated by multiplying these factors with the nominal load of the objects.

Table 6.6  Energy factor definitions

<table>
<thead>
<tr>
<th>Factor</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational factor</td>
<td>Ratio between the required number of operational components in a condition and the total number of installed components. For example: ½, operation of half the number of installed components is sufficient in the specified operational condition: the object is fully redundant.</td>
</tr>
<tr>
<td>Load factor</td>
<td>Ratio between the instantaneous load in the specified operational condition and the nominal load</td>
</tr>
<tr>
<td>Simultaneity factor</td>
<td>Ratio between the operating time and total duration of the condition. For example: 0, then object is not in operation in the specified operational condition.</td>
</tr>
</tbody>
</table>

Level of precision Energy Conversion model

The load of objects in the different conditions is for a large part based on shallow knowledge. This is especially valid for the values for the operational-, load- and simultaneity factors. Using the practical experience of a submarine officer, these values have been evaluated systematically [Pel 1995b].

The load of the energy conversion systems is for a large part based on deep knowledge. Using the physics of a conversion process, theoretical efficiencies can be calculated.

The discriminative and manipulative ability of model parameters are typically high for parameters which determine the number of installed components. High discriminative
but low manipulative abilities describe technical constants, such as the mean pressure in the hydraulic system. The hydraulic energy consumption is measured in the unit ‘litres per minute’, based on this mean value.

Example
The above presented model can be demonstrated by an example which presents the effect on nominal loads of energy conversion systems, when an additional heatload is supplied to the conditioned air. The heatload in this example increases the nominal load of several conversion systems. The effect is especially large when two or more conversions are required before the energy can be supplied in the required format.

The additional heatload is supplied to the air conditioning unit by a flow of conditioned air. This air flow contains the heatload of components cooled by the air in the conditioned space. To transfer the additional heatload from the components to the air conditioning unit, requires an increased air flow.
Increasing the conditioned air flow effects the ventilation system, air conditioning units, chilled water circulation system, chilled water plant, cooling water system and a DC to AC 440V@60Hz conversion system. All these systems consume more energy due to an additional heatload in the conditioned spaces. A more detailed description, is presented by van Diermen [1995] as part of the SUBCEM project.

6.2.2 Models for inboard space and weight sizing
The purpose of the inboard sizing model is to determine the space and weight properties of the inboard spaces on basis of objects which are allocated to these spaces. As the contour of the inboard space is specific for submarines, it introduces a number of space characteristics. These characteristics are analysed by observing general arrangements of existing designs. Figure 6.2 shows an example of a general arrangement.

Figure 6.2  General arrangement of a 3000 ton submerged displacement submarine
The following observations are made with regard to the structure:

- The cross sectional contour of the primary structure is cylindrical.
- Truncated cones are applied between the different cylindrical parts.
- Enclosures at the front or aft end of the primary structure can either be flat, hemi- or tori-spherical.
- The space in the primary structure is divided horizontally by flat bulkheads. The bulkhead at a cone is commonly located at the small cylinder end, as this location is preferable from structural point of view.
- The space in the primary structure is divided vertically by decks.

The contour of the primary structure introduces a number of space occupation characteristics, which can be observed when analysing the general arrangements. The following observations are made with regard to installation of components in spaces:

- Relatively large components compared to the dimensions of the space are difficult to locate successfully.

The required amount of space increases when a component with small dimensions is located within a space which could be used for locating a large component, see figure 6.3.

![Diagram showing cell length, sum of both objects, and maximum of both objects.](image)

**Figure 6.3**  Small and large component in cross section of pressure hull

- The area, length or width of space between frames can not always be used for locating components.
- For good accessibility, small components are distributed along area and volume of the space.
- Due to the cylindrical cross section in which frequently box shaped components are located, there are often volumes not occupied by any component.

The inboard sizing model has to comply with these observations. Consequently, the determination of the volumetric size of the inboard concept is not a straightforward summation of volumes. A model is introduced which complies with the observations.
for calculating the space sizes of the inboard concept. The description of this model contains two parts: the representation of the inboard space and the sizing algorithm based on allocation of inboard objects.

**Representation of inboard spaces**

The inboard spaces are specified by the designer using cylinder segments. Figure 6.4 shows an example of these spaces. As a consequence of this representation, a cell is defined along the total length of a compartment and the height of the cell defines the deck-height, which must be sufficient for allocating objects.

![Spaces](image)

*Figure 6.4  Definition of spaces*

This representation enables three features:

- Compartments and cells can both be defined as 'brothers'. Brothers have respectively the same compartment diameters or the same cell heights.
- Compartments and cells can be added to, moved within or deleted from the concept. For compartments these actions include their accommodated cells (with objects), while for cells these actions include their accommodated objects.
- The size of the cell can be adjusted dependent on its included objects, using a *soft* compartment length definition.

To simplify the representation of truncated cones and/or domed bulkheads, the cylindrical compartments are elongated and are called 'equivalent spaces'. An *equivalent inboard space* is a cylinder which contains the same amount of gross volume as the real compartment. Figure 6.5 shows an example of equivalent spaces.

![Cone/dome plus equivalent volume, longitudinal cross section](image)

*Figure 6.5  Cone/dome plus equivalent volume, longitudinal cross section*

This simplification enables a less complex volume and area sizing algorithm. The simplification to equivalent space is not made for calculating the length in a space.
When cones and/or domes are applied the error made in the prediction of the length is large due to the required width and height of the object, see figure 6.7.

After specifying the spaces the structural elements are considered. The observation that the area, length or width of space between frames cannot always be used for locating objects, requires the introduction of two space definitions: gross- and net-space. The net space includes all the volume within the shell of the primary structure without the volume between the frames of the structure. Frames can belong to the pressure hull, deck, or bulkhead structure. The gross space includes all the volume within the shell of the primary structure. Figure 6.6 shows both type of volumes.

![Figure 6.6 Gross and net space in transverse cross section](image)

**Allocation algorithm of inboard objects**

Each cell is sized, based on the objects allocated to the cell. The object space properties volume, area, length, height and width determine the required space in a cell. This required space can only be allocated to the free space of a cell. The free space is defined as the available space in a cell minus the space occupied by all foregoing objects allocated to the available space. When an object occupies an area, all the volume above that area is automatically occupied, notwithstanding some of that volume is not occupied by the object volume. This non-occupied volume above occupied area is only free for objects which possess the attribute ‘FreeVolIncl’. Available space is defined as the total amount of volume, area and length in a space with sufficient width and height for allocating the object. Note that area is not necessarily equal to width times length and volume is not necessarily equal to area times height. For objects which possess the attribute ‘VolBetwFrIncl’, the available volume includes the volume between the frames of the structure.

Representation of the object contours by numerical values for space characteristics, supports non-specific allocation of objects to spaces. As discussed in chapter five, non-specific allocation algorithm is applied as it improves the ability of rapid and effortless changing a general arrangement. Frequently changing an arrangement during the conceptual design stage makes this ability important. However, non-specific allocation
limits the topological knowledge about a design. To overcome this limitation a number of assumptions are made for each of the three object-types.

Assumptions made for type 'one' objects (defined by height, length, width, area, volume, mass, x-centroid and z-centroid):
From the observation that large components are difficult to locate successfully, the following assumption is defined:
  • The objects can only be located after and before each other.
From the observation that the available area, length, width and height of space between frames cannot be used for locating (large) components, the following assumption is defined:
  • Available area, width and length and height are measured in the net space

Assumptions made for type 'two' objects, (defined by height, area, volume, mass and z-centroid):
From the observation that small components do not require a fixed contour for an area, the following assumption is made:
  • As long as the free volume and area is sufficient, then the amount of length and width in a space are always sufficient.
From the observation that small components are distributed along the available area of a space, the following assumption is made:
  • The global x-centroid of the object is at the same location as the mid of the equivalent space.

Assumptions made for type 'three' objects, (defined by height, volume and mass):
From the observation that small components do not require a fixed contour for an area and volume, the following assumption is made:
  • As long as a cell has sufficient free volume, then the amount of length, width and area in a space is always sufficient.
From the observation that small components are distributed along the volume a space, the following assumptions are made:
  • The global x-centroid of the object is at the same location as the mid of the equivalent space.
  • The global z-centroid of the object is at the same location as the mid of the available equivalent space

The inboard space sizing algorithm uses the above assumptions to determine the required volume, area and length in a space. The following summary presents a short description of the inboard sizing model. More details are described in the specifications for the program SUBSPACE [vd Nat, 1996c].

The inboard space sizing algorithm distinguishes separate sizing algorithms for length, area and volume. These space algorithms are only applied when the object requires an amount of one of these types of spaces. For example, for a type one object all these algorithms are applied in the sequence: length, area and finally volume sizing.
**Length sizing**
The length sizing algorithm calculates the minimum length of a cell to accommodate the length requirement of objects. The available length in a cell is occupied, starting from the aft of the cell, in sequence of allocating objects with length requirement. The required length of an object can only be allocated to the free length of a cell. The free length is equal to the available length minus the occupied length. The available length is the maximum length in the cell having a width and height larger than required by the object. The occupied length is the length from the after most position in the cell to the front position of the occupied length of the foregoing allocated objects.

![Diagram of length sizing](image)

*Figure 6.7 Size of cell is determined by length of object*

**Area sizing**
The area sizing algorithm calculates the minimum area of a cell to accommodate the area requirement of objects. The available area in a cell is occupied, starting from the aft of the equivalent cell, in sequence of allocating objects with area requirement. The required area of an object can only be allocated to the free area of a cell. The free area is equal to the available area minus the occupied area. The available area is the area in the cell having a height larger than required by the object. If the width within the available area is smaller than required by the object, then allocation is not possible. The occupied area is the area of all foregoing allocated objects.

![Diagram of area sizing](image)

*Figure 6.8 Size of cell is determined by area of object*
**Volume sizing**

The volume sizing algorithm calculates the minimum volume of a cell to accommodate the volume requirement of objects. The available volume in a cell is occupied, starting from the aft of the equivalent cell, in sequence of allocating objects with volume requirement. The volume of an object is allocated to volume above the area occupied by the object. If the object possesses the attribute ‘VolBetwFramesIncl’ the volume above this area is calculated using the gross equivalent space. The volume can either be smaller or larger than the required volume. In the first case more volume above free area is occupied until sufficient volume is achieved. In the second case the available volume minus the occupied volume is added to the free volume. This free volume can be occupied by objects possessing the attribute ‘FreeVolIncl’.

![Diagram of volume object above equivalent area](image)

**Figure 6.9** Size of cell is determined by volume of object

After sizing these space properties the centroids of the object masses are calculated.

**Centroids calculation**

For type 2 and 3 objects the z-centroid relative to the object (local system of coordinates) is defined. After allocating the objects to spaces, their centroids relative to the boat (global system of coordinates) are determined. The calculation of the global z-centroids depends on the cross section of the space to which the object is allocated. Figure 6.10 shows the different calculations.

![Diagram of z-centroid in 5 different situations](image)

**Figure 6.10** Z-centroid of an object in 5 different situations

75
For type 1 the local x-centroid is defined. The global x-centroid of the object is equal to the local x-centroid relative to most aft location of its occupied length in the global system of coordinates.

Two examples are presented to visualise the sizing algorithms. The first example shows the allocation of two type 1 objects, the second example shows the influence of changing the allocation sequence on the required amount of space.

**Example: allocating two type 1 objects**

As an example of this algorithm, a visual representation is given of the allocation of two objects, both having volume, area, length, width and height requirements (type 1), see figure 6.11. The first situation represents the cell with one allocated object. In the next situation the second object is allocated. To accommodate this object, the free length of the cell must be equal or greater than the object length. Depending on the height of the object and the area occupied by objects placed earlier, a free area for the second object within the available area can be determined. The available area within the cell must be equal or greater than the required area for the object. The volume above the area occupied by the object must be equal or greater than the required volume.

![Figure 6.11 Allocating two type 1 objects: cell length grows due to length balance and not due to area or volume balances](image)

**Example: changing the allocation sequence**

From the observation that large components are more difficult to locate than small components the following recommendation is made:

- Allocate first the object to a space with the largest space requirements.
The effect of changing the allocation sequence on the required space size is visualised by the figure 6.12. If the smaller object is allocated to the space, more space is required to allocate the larger object than when the sequences is reversed.

![Allocation sequence type 2 objects](image)

**Figure 6.12** Effect of allocation sequence: note object with large/small space requirements

### 6.2.3 Models for inboard structure sizing

The purpose of the inboard structure sizing model is to determine the space and weight properties of the primary- and secondary inboard structure.

The *primary structure* is sized to withstand the pressure difference between seawater pressure and atmospheric pressure inboard. The primary structure is built from various combinations of thin walled cylinders, cones and domes. When a thin walled structure is subjected to external pressure it can suffer instability at a pressure only a fraction of the pressure causing yield. For metallic structures this instability can include overall hull buckling, and/or local plating or frame buckling/tripping. Figure 6.13 displays these instabilities.

![Overall frame-shell collapse](image)

**Figure 6.13** Overall hull buckling, and/or local plating or frame buckling/tripping

Several types of structure for supporting cylindrical shells described in literature are: T-framed ring stiffeners, double hull, sandwich, toroidal or swedged stiffeners [Gorman, 1991][Yuan, 1991]. However, this analysis is limited to T-framed ring stiffened shells, as this structure is commonly applied in existing submarine structures.
To size the uniformly ring stiffened cylindrical and conical parts of the primary structure, practical design standards can be used, such as the British BS5500 code [1994]. These standards consider all likely modes of the above mentioned instability phenomena. The underlying structural mechanics are described in detail in numerous papers and books [Kendrick, 1970/1994] [Faulkner, 1983] [Pegg, 1987] [Nash, 1995]. The solutions for the buckling problem are not discussed here, only a summary of the design philosophy to derive a solution is outlined.

Groen and Kaminski [Groen, 1996] developed and implemented, as part of the SUBCEM project, a tool which is based on minimizing an objective function using a nonlinear optimisation algorithm. The optimisation of this function is restricted by the collapse modes and maximum available height for inboard frames. Below, each of the collapse modes are discussed, using the references which are found in [Faulkner, 1983].

The first type of collapse is due to interframe buckling. The lower bound values of the interframe collapse pressure can be predicted by a relation based on experimental data [Kendrick, 1970]. In this relation the experimental interframe collapse pressure is related to the elastic interframe buckling pressure of an unsupported cylinder (between two frames) under radial and axial load [von Misses, 1914]. Both pressures are made non-dimensional using the pressure at which the circumferential stress at mid bay and mid thickness of the shell reaches yield [Wilson, 1966]. The uncertainties in the accuracy of the prediction are expressed by an interframe collapse safety factor on the maximum pressure.

The second type of collapse is due to overall buckling. Bryant [1954] predicts the overall elastic buckling pressure of a perfect ring stiffened cylinder by the sum of: the elastic collapse pressure of a ring frame and elastic buckling of an unsupported cylinder (between two non-imaginary bulkheads) under radial and axial load [von Misses, 1929]. The ring frame includes the adjacent shell with an effective length in an infinite long compartment [Bresse, 1866].

The overall collapse is sensitive to out-of-circularity, as it introduces additional bending stress in the frames. The total stress in the frame is the sum of the maximum circumferential stress [Wilson, 1966] plus the additional bending stress from the worst out-of-circularity [Timoshenko, 1936].

Comparison studies [Pegg, 1987] show that the prediction of overall buckling gives good results, however they are unconservative for relative short compartments which fail with circumferential wave numbers greater than three. The uncertainties in the accuracy of the predictions are expressed by an overall collapse safety factor.

The third kind of buckling is sideways buckling of frames also called tripping. This type of buckling can be avoided by providing limits on the slenderness ratios of the webs and flanges of the frames [Faulkner, 1983].

The purpose of the optimisation algorithm is to minimise an cost function with respect to the variables: shell thickness, web depth and number of frames. The cost function
The contour of the outboard spaces is governed by a compromise between on the one hand a smooth pressure distribution along the contour of these spaces and on the other hand the need for a certain amount of volume for the pressure hull and outboard located objects, such as primary ballast tanks, sonar domes etc. As a consequence, the first requirement determines the contour of each of the outboard spaces and the second requirement determines the size of these spaces. To determine the contour and size of the outboard spaces which fulfill the above requirements, for each type of space a different set of assumptions is defined.

Assumptions made for the outer hull:
From the observation that the outer hull is a streamlined envelope around the primary structure the following assumption is made to simplify its cross section:
- The cross sectional contour of the outer hull stern and bow is axis-symmetrical.

From the observation that a submarine has one outer hull which accommodates the total primary structure, the following assumptions are made:
- The contour and maximum size of the cross section of an outer hull is determined by the pressure hull at midship cross section of the boat. The size of the cross section decreases from maximum to zero along the length of the boat, however its contour does not change.

From the observation that the distance between the primary structure and the secondary outer hull structure is zero or larger than a minimum distance, the following assumption is made:
- Not more than one critical point in the entrance and one in the run section contour can exist, see figure 6.16.

Assumptions made for the added hulls:
From the observation that the added hull is an additional streamlined space, which is attached to the outer hull, the following assumption is made:
- The contour and size of the cross-section of an added hull is defined at the maximum cross section of the outer hull. The size at other locations along the length of the outer hull is proportional to the cross section area of the outer hull.
From the observation that an added hull of a submarine is usually not extended beyond the length of the pressure hull, the following assumption is made:
- The added hull is defined along the total length of the pressure hull.

Assumptions made for the appendages:
From the observation that an appendage is defined directly on an added-or outer hull or directly on the primary structure the following assumptions are made:
- An appendage defined on an added hull has the same cross sectional centre line as the added hull
- An appendage defined directly on the primary structure can not be located on a conical section.

The outboard space sizing algorithm uses the above assumptions to determine the occupied volume and weight. For each type of outboard space an algorithm is developed, which is described below.

Outer hull sizing
The volume within the outer hull can be calculated using numerical or mathematical methods. Numerical methods like Simpsons’ rule, are applied for any contour of the body, while mathematical methods require a mathematical description of the contour. However, the mathematical method is preferred as it requires less input and computation time than numerical methods. Examples, using these descriptions can be found in literature: Williams [1962] and Jackson [1983]. Williams introduced a polynomial of sixth degree which describes the longitudinal contour of the boat as whole. Jackson introduced a super-ellipse which describe the longitudinal contour of an entrance, middle and run section separately.

The less complex super-ellipse is used to describe the outer hull. However, if true ellipsoid and parabolas are used, the entrance and run section would be too fine to represent the longitudinal contour of a submarine. The fullness of the contours can be adjusted by increasing the exponents in the super-ellipse relation. The description by Jackson is simplified by Stapersma [1992], who fixed the value of one exponent in the super-ellipse relation. The other parameter offers enough freedom to select any shape.

\[
\left( \frac{l}{L} \right)^p + \left( \frac{r}{R} \right)^q = 1
\]

Entrance: \( r = R \left[ 1 - \left( \frac{l}{L} \right)^{p/2} \right] \), with \( q = 2 \)

Run: \( r = R \left[ 1 - \left( \frac{l}{L} \right)^{p} \right] \), with \( q = 1 \)

R : Maximum radius
L : Length section
r : Local radius
l : Local distance from front or aft end

82
To interpret the value of the exponent ‘p’ value in the above relations, this exponent can be rewritten into a prismatic coefficient or alternatively for the run section a tail angle. *Prismatic coefficient* is defined as the ratio between the volume in the section and the volume in a cylinder with equal maximum cross-sectional area and length. The *tail angle* is defined as the angle between the tangent of the longitudinal cross section and the longitudinal centre line of the outer hull at the aft end. The value of this angle is limited to about 20° to avoid flow separation [Loid, 1983].

For given prismatic coefficient or tail angle, maximum radius and length of the section, the SUBSPACE specifications [Nat, 1995] provide algorithms to calculate the volume, centroids and area for each section. Most of these algorithms are algebraic equations, only the area of the body with ellipsoid contour applies a numerical method.

Figure 6.16 shows an outer hull contour, which is derived by the above presented description. The pressure hull in this figure shows potential critical points. Each can be used to determine either the prismatic coefficient, maximum radius or length of the section, if one of these is not provided.

A *critical point* is defined as the location at the outer hull structure where the distance between this structure and the pressure hull structure is equal to a defined minimum distance. The entrance and run section possess both only one critical point. Figure 6.16 shows an example of possible critical points along the longitudinal contour of the pressure hull and both actual critical points along the contour of the outer hull.

![Diagram of outer hull parameters](image)

Figure 6.16 Definition of outer hull parameters

After sizing the outer hull, only type ‘three’ objects can be allocated to the space between the primary and secondary outer hull structure. The outer hull space is divided into two parts: space before (fore body) and behind midship cross section of the boat (after body). The midship cross section is defined as the middle of the cylindrical section. To calculate the space efficiencies, the outer hulls is divided in longitudinal
direction into 'slices'. The thickness of the slice is taken half the frame distance of the outboard secondary structure. To simplify the calculations, each 'slice' is allocated to only one type 3 object. If the object does not require the total available space in the slice than the remaining space is called 'lost' space. Consequently, a larger number of smaller slices decreases the amount of lost space, however it increases the computational effort.

If the object requires a height, then the object can only be allocated to the stern or bow section of the outer hull. The available height is equal to the mean outer hull diameter of the space which is occupied by the object.

Typical objects located in the fore body are: torpedo tubes, anchor housing. Typical objects located in the after body are: rudder shafting and bearings. Space not occupied by objects has to be free flooded. This space must be as small as possible as it does not contribute to the performance of the boat.

**Added hull sizing**

If the outer hull does not provide enough space around the pressure hull, then one or more added hulls can be defined. The *added hull* provides a volume which protects objects which are located outside the pressure or outer hull.

Figure 6.15 shows the different contours of the added hull cross section. The cross section can be defined at any location around the pressure hull, by defining its rotation angle. If more than one added hull is defined, then they are not allowed to cause spatial overlap. Figure 6.15 also shows that the space between the primary and secondary outer hull structure can be part of the added hull space. This feature is commonly applied in existing double hull submarines.

Using the assumption that the contour of the added hull cross-section contour does not change along the length of the outer hull, and the size of its cross section area changes linear with the cross section area of the outer hull all space properties of the added hull can be predicted. The SUBSPACE specifications [van der Nat, 1995] provide the algorithms.

After sizing the added hull, objects can be allocated to either the space before (fore body) or behind midship (after body). If the object requires height, then the available height must be larger then the object height. The available height is equal to the mean height of the added hull which is occupied by the object.

**Appendage sizing**

The *appendage* provides a volume with a hydrofoil contour. One or more appendages can be defined on the outer- or added hull structure or on the pressure hull. If more than one appendage is defined, then they are not allowed to cause spatial overlap. Figure 6.17 shows an example of a definition on the outer hull and on the pressure hull. This figure also shows that the appendage defined on the pressure hull occupies a part of the outer and/or added hull space.
Figure 6.17 Appendage on pressure hull (sail)

To simplify the sizing calculations, the volume of the appendage is represented by an equivalent box, having a length equal to the mean chord, width equal to the equivalent thickness, and height equal to the span. The SUBSPACE specifications [van der Nat, 1995] provide the algorithms for predicting the space and weight properties of an appendage.

After sizing the appendage, objects can be allocated to the available space. If the object requires height, then the available height must be larger than the object height. The available height is equal to the height of the appendage.

6.2.5 Models for outboard structure sizing
The secondary outboard structure subdivides the outboard space and provides structural support to components. The sizing model is limited to the prediction of the mass. The mass prediction of the outboard structure assumes that the required amount of mass is proportional to the total equivalent shell area. The required volume of the structure must be included in the space properties of the objects.

6.3 Models for balancing

The purpose of the submarine balancing model is to balance the component properties. This paragraph concentrates on the models for balancing the space, weight and energy properties.

The purpose of the space balance model is to compare the available space to the required space both for in- and outboard spaces. A design is only viable when for all spaces the available space is equal to or larger than the required space. The available inboard space can be defined by fixed (Hard) dimensions or by adjustable (Soft) dimensions. Fixed space dimensions are set by the designer and using these dimensions the model prevents allocating an object when not enough space is available to
accommodate the object. Adjustable dimensions can be applied for inboard spaces by elongating the length of the compartment to assure that enough free length and/or area and/or volume is available to allocate all defined objects to the cell.

The purpose of the weight balance model is to compare the weight to the displacement. A design is only viable when the total weight equals the total displacement for a defined seawater density, and the centroid of the weight is straight below the centroid of displacement. The total weight and centroid can be adjusted by the amount and location of ballast. The amount and location of the ballast must be accepted by the designer as they indicate the viability of the design. Note, that no distinction is made (yet), between fixed ballast, such as lead or variable ballast, such as seawater.

The purpose of the energy balance model is to compare the amount of available energy of each type to the amount of required energy of that type in each operating condition. During the sizing process, four relevant operational conditions are defined and the amount of available energy in these conditions is equal to or larger than the required amount. If any other operational condition requires more energy, then the maximum available amount can be adjusted by changing the nominal load of the components fulfilling the energy conversion function.

6.4 Models for performance prediction

The purpose of the submarine performance model is to predict the magnitude of fulfilling the main submarine functions as presented in chapter three: (1) Carrying platform, (2) Manoeuvring, (3) Energy supply, (4) Ship management, (5) Navigation and Observation, (6) Communication, (7) Life support, (8) Special (military). Models for predicting the performance of the ship management, navigation, observation, communication, and Special (military) functions are beyond the scope of this thesis.

6.4.1 Carrying platform

The purpose of the performance model of the components fulfilling the carrying platform function is to determine the package efficiency of the spaces. As explained in chapter three, the package efficiencies quantify the ratios between the maximum amount of available space and the occupied amount of space for both the in- and outboard spaces.

The inboard package efficiencies are determined for each cell, compartment and pressure hull after allocating the objects. The efficiencies include: volumetric-, area- and length efficiency relative to both the gross and net space. The inboard package efficiencies express the ratio between the occupied space and the total available equivalent space in the cell, compartment or pressure hull.

The outboard package efficiencies are determined for both forward and aft section of the outer hull, both forward and aft section of each added hull and each appendage.
Outboard package efficiency expresses the ratio between the occupied volume and the total available volume.

Depending on the components and on the contour and size of the space, a certain package efficiency will be feasible. Values of these efficiencies can be found by analysing existing vehicle designs [Daniels, 1996]. In general the area efficiency is more important than volume efficiency, as most components require an effective deck area with a defined clear height. Consequently, arrangements that provide more deck area per unit volume will result in smaller submarines. Chapter eight presents package efficiency values of an existing submarine.

6.4.2 Maneuvering
The purpose of the performance model of the components fulfilling the maneuvering function is twofold: first the hydrostatic performance and second the hydrodynamic performance of the submarine.

Hydrostatic performance
The hydrostatic performance includes the prediction of the submerged intact static neutral buoyancy, trim, righting moment capability and surfaced reserve of buoyancy. The neutral buoyancy and trim capability is dependent on the ratio between the mass of the fixed and variable ballast and the location of these masses. The capability of the variable ballast system can be expressed by a trim-polygon, as explained in chapter three. The capability is sufficient when the polygon encloses the loading conditions also called 'equilibrium points'. Usually, at least two conditions are considered: Full and Empty. Full and Empty are defined by the designer, in which some of the components are partly or fully consumed. When the polygon cannot enclose the equilibrium points, fixed stability-ballast must be shifted along the length of the boat or the ratio between the fixed and variable masses must be changed. Any combination of alternations can be made, however all equilibrium conditions shift in the same manner, thus care must be taken that shifting one point into the polygon does not result in shifting out other points.

The righting moment capability is dependent on the distance between centre of gravity and metacentre corrected for free surface of tankage, as explained in chapter three. The capability is sufficient when this distance is within a defined range, for example 3 to 4 percent of maximum pressure hull diameter [Burcher, 1994], without free surface effects. Note that free surface effects can cause about 10% decrease of the calculated value. By adjusting the location of the fixed stability ballast along the height, the centre of gravity can be influenced. For example, when the predicted value is below the lowest defined value, the mass of the stability ballast has to be shift downward.

The reserve of buoyancy of an intact submarine is dependent on the weight of Main Ballast Tank water and the weight of the boat in surfaced condition, as explained in chapter three. The mass of the boat in surfaced condition excludes the mass of the water within the Main Ballast tanks but includes the mass of the fixed ballast and depending on the condition a mass of water in the compensation tanks. Normally the
reserve of buoyancy must not be lower than 10% to provide sufficient freeboard, but also to enable to reach the surface in case of a critical leakage.

Hydrodynamic performance
The hydrodynamic performance model includes the prediction of submerged dynamic stability and dynamic control manoeuvring characteristics in vertical and horizontal plane.

Hydrodynamic stability
The hydrodynamic stability characteristics can be expressed by so-called vertical and horizontal stability indices [Dent, 1987]. These indices represent conditions for obtaining negative real parts of the eigenvalues of homogeneous lateral and longitudinal linearised equations of motion. The conditions are acquired from Routh's criteria applied to the characteristic equation of eigenvalues. The equations of motion for a submarine are explained in detail by Humphrey [1976]. The calculation of hydrodynamic coefficients within these equations is based on the principle of dividing hydrodynamic and gravity forces into components acting on hull, propeller and appendages [Dent, 1987]. The most important interference effects between these components are included, for example the trailing vortices from the tips of lift generating sail and bow planes on the hull and the aft planes.

Hydrodynamic manoeuvring
The hydrodynamic manoeuvring characteristics are expressed by speed and so-called effectiveness of the control appendages on the heave, pitch, sway and yaw motions [Dent, 1987].

The first hydrodynamic manoeuvring characteristic, 'speed', of the submarine is dependent on the hydrodynamic drag and the available effective propulsion power. The hydrodynamic drag of a submerged submarine can be divided into the drag of the hull and the drag of the appendages. However, the combined drag is somewhat larger, this additional drag is called interference drag. The drag of the hull is the sum of the skin-friction drag and pressure drag of the hull. The drag of each defined appendage is the sum of the skin-friction drag and pressure drag of the appendage, plus the interference drag. The model for predicting all these kinds of drag is presented in detail by Holtackers [1993], Pel [1995a] and Van der Nat [1996d].

To minimise the submerged drag for a given envelope volume of the hull, both the wetted area and the curvature of the longitudinal contour must decrease to reduce respectively the skin friction and pressure drag. Wetted area and curvature of contour are mainly influenced by two hull parameters: the fineness ratio (Length/Diameter) and prismatic coefficient. This effect can be shown by varying each parameter. Using the relations in [Pel, 1995a] the combination of the pressure- and friction drag produces a minimum value of total drag at a fineness ratio of approximately 6-7 and at a prismatic coefficient of approximately 0.60-0.62.

To minimise the drag of a given envelope volume of an appendage, a cross sectional profile with a low drag coefficient must be chosen, the root thickness must decrease,
the root chord length must increase and the span must decrease [Oele, 1993]. Further reduction is possible by applying a so-called fillet at the root of the appendage [Hoerner, 1965].

The hydrodynamic drag of a snorking submarine includes besides the submerged drag also a wave making resistance and for each lifted mast, a mast resistance. The model for predicting the wave making resistance is derived from model tests [Holtackers, 1991]. To minimise this resistance for a given hull, the snort draught must be increased. However, usually the snort draught is limited by the maximum height of the appendage which contains the masts. This height can be calculated using the maximum stroke of the masts, which is limited by the available space or sometimes by vibration problems [Heggstad, 1981]. The maximum height of the appendage is limited by either the maximum generated snap roll, its resistance or structural weight. The model for predicting the mast resistance includes the drag of friction, pressure, interference and surface piercing components [vd Nat, 1996d]. To minimise this resistance for a given mast diameter and wetted length, a mast fairing must be applied.

The model for predicting the effective propulsion power can be divided into three separate parts: prediction of the direct current power to mechanical power conversion efficiency of the main electric motor, the mechanical efficiency of the mechanical transmission and overall propulsion thruster efficiency of the propeller. The conversion efficiency of the main electric motor is dependent on the no-load and load losses. The no-load losses are caused by: magnetic hysteresis in the armature iron, magnetic pulsation in pole shoes, the friction in brushes and bearings and the Joulean heat in the excitation windings. The load losses are caused by: Joulean heat in the brushes, armature- and interpole windings. The efficiency is determined for the maximum continuous condition. For other conditions the efficiency can be determined by either an assumed parabolic part load curve [Pel, 1995a] or by using a detailed model for the load-losses [vd Nat, 1996d]. The first model can be utilised successfully when the design of the Main Electric Motor is analogous to the design(s) which validate the parabolic part load curve. However, when the design involves new (improved) values for technological constants then the more detailed model can be utilised successfully.

For a current larger than the maximum continuous current, the Joulean heatload is larger than the cooling capacity of the circulating cooling-air. To determine the maximum endurance of thermal overload the following assumptions are made:

- the maximum duration is restricted by the maximum allowable temperature of the armature winding insulation material.
- the thermal capacity is limited to the armature windings, the heating curve is exponential.
- the heat transmission between the windings and the cooling water is constant per unit temperature difference.

Using these assumptions, for each initial temperature of the windings a maximum duration can be calculated [Pel, 1995a].
The mechanical transmission efficiency is the ratio between the power delivered to the propeller and the power delivered by the propulsion driver. This efficiency can be divided into bearing and thrust block efficiencies. The bearing efficiency can be related to the rotation rate of the shaft, when a constant friction coefficient is assumed. The thrust block efficiency is related to the rotation rate of the shaft and an additional thrust due to diving pressure on the aft end of the shaft [vd Nat. 1996d]. The thrust delivered by propulsion driver can be related to the rotation rate squared when the advance ratio is assumed to have a constant value.

The total mechanical efficiency at maximum continuous condition is usually taken equal to 0.98, although heatload measurements of the thrust block seems to indicate a somewhat higher value.

The overall propulsion thruster efficiency includes the hull efficiency, open water efficiency and relative rotative efficiency. Each efficiency is discussed below.

The hull efficiency is the ratio between the effective propulsion power and the propulsion power delivered by the propeller. The effective propulsion power is equal to the work done in moving the submarine at a speed against a resistance. The power delivered by the propeller is equal to the work done in delivering a thrust at a speed of advance in the propeller disk. This efficiency is not a true efficiency, as the effective propulsion power can be larger than the power delivered by the propeller due to the amount of energy that can be retrieved from the wake. The hull efficiency ratio can also be rewritten in Taylor notation by the ratio between the factor expressing the thrust deduction and a factor expressing the free-stream water speed reduction at the propeller disk. In literature, the thrust deduction factor and free stream reduction factor are represented by respectively the value one minus the thrust deduction fraction and one minus the nominal wake fraction. Different models to predict the thrust deduction and nominal wake fractions are presented by Holackers [1991][1992][1993b]. These models are based on model tests, and include the effect of hull fullness, ratio between propeller- and hull diameter, rudder configuration and boundary layer thickness as expressed by Reynolds number.

The open water efficiency is the ratio between power delivered by the propeller and the power to drive the propeller in open water with a uniform water inflow at a speed of advance. To predict this efficiency the open water characteristics of the Wageningen B-series are used [Oosterveld, 1975].

The propeller characteristics are predicted by optimizing the open water efficiency within the B-series propellers for defined number of blades and open water torque at a rotation rate in burst condition. The propeller characteristics to be optimised are: diameter, blade area ratio and ratio between pitch and diameter. The blade area ratio is limited by the cavitation phenomena, the minimum value can be determined by applying Keller’s cavitation criterion.

The relative rotative efficiency is the ratio between the torque of the propeller in open water condition and the torque in the behind submarine hull condition. This efficiency expresses two differences: first the difference between the wake field and second the difference between the relative amounts of turbulent flow on the propeller blades. For a single screw submarine the turbulence in the water behind the hull is greater than that
in open water, normal values are in the region from 0.95 to 0.99 [Holtackers 1991].

The second hydrodynamic manoeuvring characteristic control effectiveness value is defined as the ratio between the hydroplane force or moment per unit deflection and the initial acceleration derivatives due to hydrodynamic and gravity forces. These ratios are non-dimensional, to enable comparison of submarines with different lengths.

A model [Dent, 1987] which predicts the dynamic stability and manoeuvring characteristics has some typical shortcomings. First, the equations of motion are based on linear derivatives, and can only be applied for small changes in the curvature of the submarine’s path. Second, no general accepted values for these indices can be given for which the degree of stability or controllability is sufficient. Due to these shortcomings, the indices can only be used to compare control performance of different submarines.

6.4.3 Energy supply
The purpose of the performance model of the components fulfilling the energy supply function is to determine the energy-autonomy of the submarine. The energy-autonomy can be determined for the total mission, or for a part of the mission. Typical parameters describing the total mission autonomy are: total endurance, total range, indiscretion rate and speed of advance. Typical parameters describing a specific part of the mission are: maximum submerged endurance, range and recovery rate. Appendix C provides a more detailed description of the energy supply performance model.

Total mission endurance and range
The total mission endurance and range is limited by the performance of ‘machinery provisions’. The provisions for the machinery contain storage tankage for operating fluids and maintenance parts. The main operating fluids include fuel, lubricating oil, hydraulic oil and distilled (demineralised) water. Table 6.6 shows the performance of the net storage capacity. The maintenance parts include the spare parts and special tools to exchange these parts. The amount of these parts determine the maintainability of the components.

<table>
<thead>
<tr>
<th>Operating fluid</th>
<th>Performance of net storage capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel oil</td>
<td>Determines the maximum amount of produced electric energy by the diesel generator sets, this amount is dependent on the fuel consumption per unit produced energy</td>
</tr>
<tr>
<td>Lubricating oil</td>
<td>Determines the maximum amount of electric energy which can be produced by the diesel generator sets, this amount is dependent on the consumption per unit produced energy</td>
</tr>
<tr>
<td>Hydraulic oil</td>
<td>Determines the hydraulic oil redundancy</td>
</tr>
<tr>
<td>Distilled water</td>
<td>Determines the number of topping ups, when the battery cell acid level becomes close to the low level.</td>
</tr>
</tbody>
</table>

Table 6.6 Performance of storage capacity operating fluids
Mission indiscretion rate

The mission indiscretion rate is the ratio between charge time and total time. Both durations are determined by the battery cell capacity for a defined discharge range. The battery capacity is defined relative to the capacity at infinite hours discharge and the (dis-)charge current. Infinite in this context usually expresses 100 hours discharge. The defined range is the difference between the maximum and minimum charge conditions, and is usually limited to a value below 10%. Using this limitation, both submerged and snorting conditions are called shallow.

The (dis-)charge current in these conditions is dependent on the closed circuit voltage at the terminals of the batteries and DC power. For discharging condition the DC power is determined by the power required for fulfilling the propulsion and energy supply function. For charging condition the DC power is determined by the difference between the power provided by the generator sets and the power required for fulfilling the propulsion and energy supply function.

Both charge- and discharge time can be predicted using a shallow (dis-)charge model [vd Nat, 1996]. This model uses a theory about the behaviour of shallow (dis-)charged batteries as presented by Stapersma [1998]. An important feature of this model is the prediction of (dis-) charge energy including the losses due to the real internal resistance of the battery cells. The real internal resistance of a battery cell is defined as the ratio between the voltage drop from closed to open circuit terminal voltage and the actual current.

By definition is the voltage drop for a mean (dis-)charge condition equal to the difference between the voltage at infinite small (dis-)charge current and the voltage at the actual (dis-)charge current. The infinite small discharge current is assumed to occur at 100 hours discharge. The voltages can be determined from the measured relation between discharge cell voltage and battery capacity as percentage of 100 hours capacity for different discharge currents.

Figure 6.18 shows an example of such a relation in full lines. This figure clearly shows the effect of slow diffusion speed of the electrolyte at high discharge currents. This effect causes a larger voltage drop and a smaller battery cell capacity at the end of discharge. The relation between maximum battery cell capacity and current is given by Pel [1995a] for different types of batteries like: Double Decker, Copper Negative Grid, Copper Stretch Material. The figure also shows in broken lines examples of constant battery capacity as percentage of the maximum capacity at the actual current. For lead-acid batteries manufacturer’s data show that the ratio between closed circuit voltage and current has an almost constant value for all conditions relative to the capacity for actual discharge current. This relation is called ‘pseudo’ internal resistance to distinguish it from the above defined real internal resistance [Stapersma, 1998].

For charge the same kind of assumptions are made to determine the voltage increase. Due to hysteresis effect the open circuit voltage during charge condition is somewhat higher than during discharge condition. The internal resistance during charging at a battery state ‘x’ relative to 100 hours discharge is assumed to be equal to the internal
resistance during discharge at a battery state ‘1-x’. Corrections on the calculated voltage drop can be made, for example to account for the non-linear voltage drop along the height of the battery cell. Note that the maximum charging voltage is limited to a value where gassing of the battery cell starts. When gassing starts the charging current must be reduced. During normal operation this charging stage is avoided as it increases the snorting time.

![Graph of voltage and capacity relation](image)

Figure 6.18 Voltage - real (dis-)charge condition, based on 100 hours discharge

**Speed of advance**
The speed of advance is the mean speed during both submerged and snorting condition. This speed is equal to the sum of snorting rate times the snorting speed and submerged rate times the submerged speed. The snorting rate is almost equal to the above defined indiscretion rate, only the time between starting the snorting operation and starting the battery charging is not included in the indiscretion rate. By definition the submerged rate is equal to one minus the snorting rate.

**Maximum submerged endurance and range**
The maximum submerged endurance is the maximum duration of a constant electric DC power discharge for fulfilling the propulsion and energy supply function in a specified condition. This maximum duration is determined by the discharge range (usually more than 10%) of the battery cell capacity relative to the actual discharge capacity and the required discharge current.

A deep discharge model can predict the maximum duration [vd Nat, 1996d]. This model uses a theory about the behaviour of deep discharged batteries as presented by Stapersma [1998]. For deep discharge the total amount of available energy is predicted by solving a differential equation which follows from combining the definitions of change in ampere hours and change in discharge state relative to actual battery capacity. The equation can be solved by an integration method, for example Simpson’s rule. The upper and lower limits of the equation are defined by the discharge range relative to the actual battery capacity. A feature of this equation is the inclusion of the derivative of the current with respect to the battery condition relative to the actual discharge capacity. This derivative is usually taken equal to zero [de Vries, 1992b], however for
constant power discharge this term should be included. The derivative has the largest effect on the (dis-)charge calculation result at the end of deep discharge.

**Recovery rate**

The submerged recovery rate is the ratio between the time required to recharge the batteries to the initial energy level by an air independent energy supplier and the total submerged time. The recovery rate is dependent on the available DC power provided by the air independent and the required power for fulfilling the propulsion and energy supply function in both submerged discharge and submerged charge condition. The submerged condition is called *Balanced condition* when the power delivered by the air independent energy supplier is equal to the total required power.

The submerged endurance and range on air independent energy is limited by the performance of net storage capacity of the air independent energy operating fluids. The performance is expressed by the maximum amount of produced electric energy by the air independent energy supplier. For example for Closed Cycle Diesel generator sets this amount depends on the fuel and Liquid Oxygen consumption per unit produced energy [Sipkema, 1993].

**6.4.4 Life support**

The purpose of the performance model of the components fulfilling the life support function is the total mission endurance, during which a defined number of crewmembers can operate autonomously without refill of any kind of life support provisions. The provisions for the crew contain potable water, provisions in cool, cold and other stores, CO$_2$ absorption material and O$_2$ candles. The relation between the amount of each these kinds of provisions and the maximum mission duration is given by Claessen [1994]. These relations are based on design standards applied by the Royal Netherlands Navy [KM, 1991]. Typically, the maximum mission endurance is limited to about 60-90 days, for large submarines with high habitability standards.

**6.5 Conclusions**

The submarine design knowledge, which is presented in chapter three, can be formulated into design models. Both existing and new models must be applied to formulate all the design knowledge for predicting the property values and performance values of the components and the boat. Table 6.7 shows for each main function a rough indication of the ratio between the amount of deep and shallow knowledge implemented in the applied design models.

Most effort has been put into models of components, which have a large contribution to the (internal) space, weight and/or energy of the submarine. As a result the models for calculating the space properties of the objects fulfilling the carrying platform, manoeuvring, energy supply and life support function are based on a high(-er) ratio between deep and shallow knowledge.
Table 6.7  Submarine design models

<table>
<thead>
<tr>
<th>Function</th>
<th>Space</th>
<th>Weight</th>
<th>Energy</th>
<th>Performance model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrying platform</td>
<td>★★★★</td>
<td>★★★★</td>
<td>Not applicable</td>
<td>★★★★</td>
</tr>
<tr>
<td>Manoeuvring</td>
<td>★★★★</td>
<td>★★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>Energy supply</td>
<td>★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>Ship management</td>
<td>★★★</td>
<td>★★★★★</td>
<td></td>
<td>★★★★</td>
</tr>
<tr>
<td>Navigation and Observation</td>
<td>★★★</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication</td>
<td>★★★</td>
<td>★★★★★</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Life support</td>
<td>★★★</td>
<td>★★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>Special functions</td>
<td>★★★</td>
<td>★★★★★</td>
<td></td>
<td>★★★★</td>
</tr>
</tbody>
</table>

Note: More black squares mean more deep knowledge is applied in the model blank cell means a model is not (yet) available

Table 6.8 gives a (limited) overview of the deep and shallow knowledge on which the models are based.

Table 6.8  Submarine design and performance models

<table>
<thead>
<tr>
<th>Function</th>
<th>Space</th>
<th>Sizing models based on:</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrying platform</td>
<td>physical dimensions of spaces</td>
<td>buckling/tripping phenomena</td>
<td>not applicable</td>
</tr>
<tr>
<td>Manoeuvring</td>
<td>mechanical/magnetic/thermal load</td>
<td>mechanical load</td>
<td>electromagnetic laws, efficiency data of built components</td>
</tr>
<tr>
<td>Energy supply</td>
<td>power, data of built components</td>
<td>density data of built components</td>
<td>Electromagnetic laws, efficiency data of built components</td>
</tr>
<tr>
<td>Life support</td>
<td>crew, data of built components</td>
<td>density data of built components</td>
<td>efficiency data of built components</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Function</th>
<th>Performance models based on:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrying platform</td>
<td>Physical dimensions of spaces and objects</td>
</tr>
<tr>
<td>Manoeuvring</td>
<td>Newton’s law, Archimedes principle, etcetera</td>
</tr>
<tr>
<td>Energy supply</td>
<td>Electromagnetic laws, capacity characteristics of built batteries</td>
</tr>
<tr>
<td>Life support</td>
<td>Efficiency data of built components</td>
</tr>
</tbody>
</table>

95
7

IMPLEMENTATION

What we shall say we have, and what we owe
Shakespeare

This chapter introduces tools for representing and reasoning with the knowledge described in the previous chapter. The first part analyses the required tool features to represent and use the acquired submarine knowledge. The important tool features: "support incremental programming" and "answer different kind of design questions with the same body of knowledge", can be supported powerfully by a tool which uses knowledge-based reasoning techniques. To fulfill the tool features, the candidate tool should integrate different aspects of the basic representation and reasoning techniques, as found in literature. However, only numerical knowledge can be represented efficiently in this way, additional procedure-based techniques are applied to representing the topological and geometrical knowledge. The second part identifies available tools facilitating the defined tool features. The third part describes the development of a prototype with the chosen tool and deals with the activities to support the operational life of the implemented knowledge such as quality assurance.

7.1 Tool features for candidate design tools

The body of submarine design knowledge has been discussed in chapter six without prior knowledge about its representation. This paragraph presents the link between the knowledge and its representations. This link requires a number of design features which must be included in any candidate tool. Note that throughout this paragraph the required tool features are prefixed with 'TF', which are used to select a tool in the next paragraph.

From chapter five is concluded that three knowledge types (numerical, geometric and topological) are used to represent the submarine design knowledge. *Representation* in this context is the formal encoding of knowledge by a defined semantic interpretation
and syntactic structure of symbols. The next sub-paragraph discusses tool features which support the representation of the submarine design knowledge.

7.1.1 Tool features for numerical knowledge
Much of the submarine design knowledge involves the formulation of mathematical parameters, relationships and conditional expressions, as discussed in the previous chapter. The tool features for representing this knowledge can be divided into the coding standards of this knowledge type, the structure within the body of numerical knowledge, and the reasoning facilities.

Coding standards
Each of the submarine’s numerical knowledge has relevant characteristics, which have to be represented into a coded format.

TF 1 The tool should be able to represent name, reference text and illustration of mathematical parameters
The body of numerical knowledge contains several hundreds of parameters. A unique meaningful name is required to distinguish each parameter, thereby avoiding inconsistencies. Inconsistencies between parameters occur when two different parameters have the same meaning, or when one parameter has two or more meanings. Each parameter has an extended text or illustration for fuller explanation of its meaning. This extended text contains background knowledge which explains the context of the knowledge and an example set of values which displays a particular interpretation.

TF 2 The tool should be able to represent the value source of mathematical parameters
The parameter values can be determined by different sources: by a relationship as output value, by the designer as input value, by the knowledge about the parameter as a constant value, or by a combination of these. When the parameter value is determined by a combination, its value can either be calculated by one source or by another dependent on the design problem. For example, a value can be calculated by one or more relationships, but it can also be provided by the designer, thereby accelerating the design process.

TF 3 The tool should be able to represent the type of mathematical parameters
The parameter values in the body of knowledge have different significance. Some parameters can have any numeric value in a continuum, while others can only have a discrete numerical value, or a choice from different text strings. These differences are expressed by parameter types, typical examples are: double precision number, boolean, string text, or matrix of numbers. The defined parameter type is important, because it restricts the operations between parameters. For example logical operations require boolean formatted parameters, while numerical operations require numbers.
TF 4 The tool should be able to represent the unit of mathematical parameters
To interpret the value of a parameter, a unit is required, such as one from the
international SI system. The choice of the unit affects the numerical value of the
parameter.

TF 5 The tool should be able to represent a valid range of mathematical parameter
values
Parameters are not just symbols, but they have a physical meaning, which involves
ranges of values in which they are feasible by physics or technological limitations. A
typical example is the mass of an object, the value of which must be positive.

TF 6 The tool should be able to represent name, reference text and illustration of
mathematical relationships
The body of numerical knowledge contains several hundreds of relationships. These
relationships represent physical phenomena or technological rules of thumb. To
distinguish each relation a meaningful description is required. All mathematical
relationships have a unique meaningful name. An extended name and illustration can
be used for fuller explanation or for more complex reference. The extended text
contains background knowledge which explains the context of the knowledge.

TF 7 The tool should be able to represent the dependency direction of mathematical
relationships
In general, each numerical relation can determine one parameter value when all other
parameters within the relation are known. The dependencies between the parameters can
be illustrated as (partly) directed networks [Serrano, 1992]. A dependency can either be
in one direction or when the inverse is valid in two directions. Entropy of the networks
[Coyne, 1989] defines the measure of fixed directions between the parameters. High
entropy implies two way directions between the parameters. Although this creates a
great creative potential, it also implies a poor computational efficiency for solving
design problems as each parameter is (strongly) connected to every other parameter.
Low entropy implies one way directions between the parameters.

TF 8 The tool should be able to represent the conditions of mathematical relationships
Numerical relations cannot always be applied, as all its conditions must be satisfied
first. Unlike physical laws, technological-based empirical relationships do not have
universal validity. Firstly there is a context in which the relation is derived and
secondly there are ranges of valid values for the parameters in the relation. Both the
context and ranges of validity should be checked before the relation is applied. If a
condition is not satisfied, a message can be passed to the designer.

TF 9 The tool should be able to represent the type of mathematical relationships
The body of knowledge contains both physical- and technological-based empirical
relations. The type of relation defines the source of data upon which the relation is
based: physical and empirical respectively.
Alternative empirical relations may exist for determining a parameter value. These relations are not like simultaneous equations in mathematics, although they may be valid simultaneously. The designer must select the most promising relations for solving the problem at hand. The other empirical relations which are able to determine the same parameter value can not be applied.

**TF 10**  The tool should be able to represent a unit check of mathematical relationships
Mathematical relations have dimensionality associated with the parameters within each relation. Physical relations have to be dimensionally consistent. Empirical relations do not necessarily have to be consistent, as they represent statistically consistent shortcuts rather than actual behaviour.

**TF 11**  The tool should be able to perform deterministic manipulation of mathematical relationships
The body of relations includes many different deterministic manipulations, such as algebraic and database operations. Typical algebraic operations are summation, multiplication but also goniometrical or truncation functions. Typical database operation is record selection by a condition, like nearest value.

**TF 12**  The tool should be able to communicate with external applications of mathematical relationships
Some knowledge is included in (existing) executable programs. Relationships can initiate the execution of these programs, running separately from the tool.

*The body of knowledge*
The body of submarine knowledge contains several hundreds mathematical relationships. The implementation and maintenance of these relationships must be supported.

**TF 13**  The tool should support incremental programming
The body of submarine design knowledge evolves during the long period of development as in the beginning the design tasks and the end product can not be completely defined. The development of a body of submarine knowledge starts with the implementation of a skeletal (global) design description. Depending on the design problem more knowledge might be required to describe the design at a higher level of detail, precision and/or scope. New knowledge parts are added continuously, however unintentional modification of already implemented knowledge must be avoided. Modular knowledge sources can support the incremental programming of knowledge. The body of knowledge is divided into modules, each describing a complete numerical model about a defined part of the design. Modularity enables independent adding, changing and/or removing of complete models. Within such a defined module the mathematical relationships are not loosely coupled, which is also recognised by Schreiber [1992]:

100
"A Knowledge base is NOT a container filled with knowledge extracted from an expert, but an operational model that exhibits some desired behaviour specified in terms of real-world phenomena" [Schreiber, 1992]

**TF 14** The tool should support multiple use of knowledge
Parts of the body of knowledge contain relationships, in which only the parameter values are different. Typically this occurs when a parameter must be calculated for different conditions. The tool has to support multiple use of the relationships, thereby avoiding multiple explicit definitions of relationships.

**TF 15** The tool should be able to present knowledge in a structured way to the user
To support fast access of already implemented knowledge, the relations and its parameters and conditions must be displayed in a structured way. Several ways of displaying the knowledge are possible:

- Listing all relationships or parameters, which enables overview and fast access to the characteristics of a specified relationship or parameter.
- Listing relations or parameters belonging to a model, which enables fast access to a complete model.
- Listing all conditions or all parameter characteristics belonging to a relationship

**Reasoning facilities**
The body of numerical knowledge can be applied to solve different kinds of design problems. The objective of reasoning is to find a sequence of relationships that transforms an initial state of parameters into a goal state. This search can be represented by finding a path through a network of nodes, in which the nodes represent the parameters and the (un-directed) arcs the relationships between them. In chapter two this network was introduced as a constraint satisfaction model. As the designer assigns values to parameters, other parameter values are derived using the relationships between the parameters. An important characteristic of this model is that each relationship can determine only one parameter value.

**TF 16** The tool should be able to support the designer while directing the undirected network
An important characteristic of the body of numerical knowledge is that the choice of in- and output parameters is not predetermined. The designer can freely set and reset values of any parameter, and the tool must rearrange dependencies in the network accordingly. The ultimate change is reversing a design problem, defining an unknown to a known parameter and reverse.
As dependencies in the network are not predetermined, the sequence of instructions cannot be coded. Rather, the order in which parameter values are assigned and which relations are selected, determines the computation that is performed and direction in the network that is followed.
The tool can support the designer by:

- Proposing valid relation(s) which can determine an unknown parameter. If more than one relation is valid, priorities determine the sequence of proposing a relationship for an underived parameter. The priorities express the way a designer makes, in general, a choice between different valid relations. The priority can be determined by meta-rules or by the knowledge engineer which gives each relation a priority. However, while directing the undirected network the designer should be able to override the relationship-ordering according to these priorities for ‘softly’ defined relations. A relation is ‘Soft’ when its application must be accepted by the designer. The designer cannot override the relationship-ordering when a relation is defined ‘Hard’, as this type of relations can always be applied.
- Providing intermediate results at any stage of the solving process.
- Displaying all parameter values, which can be determined by the current achieved network.

TF 17 The tool should have facilities for error handling, when it encounters logical inconsistent or incomplete knowledge during the search process. The body of numerical knowledge can contain too many or too few relations for performing a design task. To avoid errors the tool should continuously check for logical inconsistency, such as determination of unnecessary rules, redundancy and conflicts between rules, but also for incompleteness, such as missing rules.

TF 18 The tool should be able to solve implicit mathematical relationships. When applying the body of knowledge, cycles in network of relations can be created. To break these cycles, the tool must solve its relations simultaneously. The smallest set of relations which can be solved simultaneously is called a strong component, as defined in chapter two. The tool must be able to recognise the strong components and solve them. To solve a strong component containing (non-)linear relations, an iterative method, such as Newton-Raphson, Jacobi, Gauss-Seidel or Broyden-Fletcher-Goldfarb-Shanno method, can be applied. In literature many books can be found describing these methods [Golub, 1992], [Hinton, 1992]. Depending on the relations within the strong component one or more of these methods are computational efficient and reliable. Computational efficiency is mainly related to the effort required to compute an iteration step and the number of iterations, for example it is advantageous to enlarge the step size when the relations are almost linear, and to decrease it for highly nonlinear parts of the solution.

The reliability is mainly related to convergence and accuracy. Convergence must occur from any given starting approximation, as well as when it is not sufficiently close to the solution. Convergence problems occur when the partial derivatives, presented in the Jacobian matrix becomes (close to) zero (ill-conditioned system of equations) or when divergence or oscillation between two or more computations of an iterate takes place. Accuracy is dependent on convergence criteria applied in the iteration method. Convergence criteria for each solved parameter in the strong component must be dependent on the magnitude of its value.
TF 19 The tool should be able to optimise numerically a single goal. Within the smallest set of relations which can be solved simultaneously (strong component) it must be possible to define a goal parameter which must be maximised or minimised by variation of one or more defined parameters. Within the variations three different actions can be distinguished: separable, inseparable and sequential [Dai, 1994]. Separable actions allow one or more parameters to vary simultaneously even if one of them is at its boundary. Inseparable actions allow parameters only to vary if none are at their boundaries. Sequential actions are variations of parameters one at a time. A variation is only successful when an optimum value for the goal parameter is found and all constraints in the strong component are satisfied.

TF 20 The tool should be able to calculate variants of a design solution. The Concept Exploration Model must be able to explore the influence of changing one or more input parameter values on the output. To recalculate the network efficiently during the parameter variation, only the parts which are influenced directly by relation(s) and indirectly by condition(s) must be recalculated.

TF 21 The tool should be able to explain how the knowledge is applied. Each design task requires directing the undirected network in a (partly) new way. To support the understanding of the found solution several explanation facilities are needed:
- Explain and show how the network is directed. To avoid misunderstanding, the explanation must be based on the same reasoning structure as the tool uses to derive the directions. This explanation is divided into step and strategic explanation. The step explanation presents the decisions and choices made in each step of the solution process. The strategic explanation presents the total reasoning structure to solve the goal. This structure contains: the relation which can determine the value of a parameter, the parameters which are influenced by a parameter, the parameter which is determined.
- Explain why achieving a (sub-)goal is needed to derive a path and show which relationships are available for solving the (sub-)goal. The priority according to the meta-knowledge determines the sequence within the presented relationships.
- Explain how a parameter value affects the outcome of the design process.

TF 22 The tool should be able to systematically store the way a solution is found for a specific design problem. To avoid redetermination of a solution which has been found in the past, the knowledge to solve a specific problem must be stored in a documented library of solved problems. This library can be used to retrieve the way a solution is found for a (partly) similar problem. As changes in the body of knowledge could have been occurred since the previous solution was found, a check on the validity of the applied knowledge must be made.

7.1.2 Tool features for geometric knowledge
The submarine design knowledge involves the formulation of size and shape of the
space required or provided by components in the boat. Using the object and space sizing model, as discussed in chapter six, enables representing the geometric knowledge by numerical knowledge. The object sizing knowledge is different from the space sizing knowledge. The algorithm for predicting the objects dimensions like volume, area, length, width and height is unique for each defined object, while the algorithm for predicting the space dimensions is identical for all spaces of one kind, such as cells, compartments, pressure-, outer-, added hulls and appendages. This distinction introduces two different approaches for representing and reasoning with geometric knowledge.

First, the object sizing knowledge involves the same formulation of mathematical parameters and relationships with conditional expression, as discussed in the previous sub-paragraph. The required tool features for representing and reasoning with this knowledge are equal to those required for numerical knowledge.

Second, the available space sizing, balancing and performance model involves a fixed procedural algorithm for each type of space. The required tool features for representing this knowledge can be divided into the coding standards and the calculation facilities.

**Coding standards**
Each space type of the submarine has characteristic geometrical properties, which have to be represented into a coded format.

**TF 23**
The tool should be able to represent and show all required geometrical space properties.
The space within the submarine is divided into six different types: cells, compartments, pressure-, outer-, added hulls and appendages. Each type is described by a set of space properties, such as length, volume, etcetera (see chapter six). These space properties must be represented and shown graphically by the tool.

**Calculation facilities**
The value of some properties must be calculated. For example, the compartment property ‘soft length’ must be calculated, based on the objects allocated to the cells defined within the compartment. The models for calculating these space properties are presented in the chapter six. The tool must be able to calculate space properties, based on the presented models.

**TF 24**
The tool should be able to (re-)calculate, with high computational efficiency, the space properties after a change in the defined properties. During the design of the submarine, changes in defined space properties influence other properties. To avoid inconsistency after each change of a geometric property value, all related properties have to be recalculated.

**TF 25**
The tool should be able to store all defined and calculated space properties.
To avoid redetermination of a solution which has been found in the past, the knowledge about a geometric feasible design must be stored in a documented library of concepts.
7.1.3 Tool features for topological knowledge

The submarine design knowledge involves the formulation of relative location of components and spaces from which a unique design is assembled. The required tool features for representing this knowledge can be divided into the coding standards and the calculation facilities.

*Coding standards*

Each space type of the submarine has characteristic Topological properties, which have to be represented into a coded format.

**TF 26** The tool should be able to add, move or delete spaces including the objects which they accommodate.

The topological knowledge, as defined in the sizing model, must be represented by a sequence of spaces and objects. When changes are made in this sequence, all spaces and objects included in the modified space are automatically up-dated.

**TF 27** The tool should be able to determine and show the position of each space and object in a global system of axes.

The location of spaces and objects are defined in relation to one point of the concept, which is defined in the global system of axis. Using this information, the tool must determine and show the location of spaces and objects in the global system of axes.

**TF 28** The tool should be able to store all defined topological space properties. To avoid redetermination of a solution which has been found in the past, the knowledge about a topological feasible design must be stored in a documented library of concepts.

7.2 Identifying candidate tools

In the preceding paragraph 28 Tool Features are described. These can be classified into two categories: those requiring knowledge-based representation and those which can use a procedure-based representation. Tool features 1 to 21 fit into a knowledge-based representation and reasoning, which are found in knowledge-based tools. Tool features 23 to 28 fit into a procedural tool, as the models which are used to represent and calculate the geometrical and topological knowledge do not contain shallow knowledge.

It is therefore not expected that these models will change much in the future. A procedure-based tool in which the model is implemented in a fixed manner can support the representation and calculations more efficiently than a knowledge-based tool.

In the following sub-paragraphs, some knowledge-based tools and procedure-based tools are described.

7.2.1 Knowledge-based tools

A *knowledge-based tool* is a software tool capable of supporting the representation of knowledge about a specific application and exploiting it through appropriate reasoning
mechanisms [Guida, 1994]. Typical for knowledge-based tools is the separation of these two capabilities. This separation gives these tools an advantage over procedure-based tools, as the knowledge engineer does not have to decide in advance how the knowledge is to be used. In procedure-based tools the procedure between in- and output is fixed. In knowledge-based tools the procedure is not fixed, as the knowledge is thrown into one big "pot" and by combining it, design problems are solved in original ways. However, separation also implies a disadvantage, as unstructured does not mean independent. Dependency can cause over-determination in a design solution which contains conflicts with earlier specifications.

Candidate knowledge-based tools can be categorised depending on the required representation and reasoning techniques. The basic knowledge representations discussed here are: production rules, semantic networks and frame hierarchies. From each discussion a few promising advantages for the candidate tool are presented.

Knowledge representation and reasoning by production rules

The knowledge representation by a collection of production rules is built from condition-action pairs. Given a production rule, the action part, also called goal, can be applied when its conditions are true. There are three principal points to note about the use of production rules.

First, the format in which the condition is expressed can use the logical connectives AND, OR, NOT together with operators like ‘equal to’, or ‘less then’. This makes the codification of knowledge straightforward, as the rules have a readily understandable format. Second, the production rule representation supports modularity, as a rule is an independent chunk of knowledge. Thirdly, the collection of rules have structure when actions are part of other conditions. These inter-relations can be shown graphically in diagrams [Hodgson, 1991]. Figure 7.1 is an example, which also shows the process of combining rules to avoid common parts in set of rules. Normalising supports the interpretation and consistency of a set of logically related rules by re_combining the rules. In figure 7.1. the statement ‘R’ in the first example and the statements ‘T’ and ‘U’ in the second example are common parts.

![Diagram of Normalising logically related rules](image)

Figure 7.1 Normalising logically related rules
Two main control structures are used to specify the reasoning process contained in a rule-based knowledge representation; backward- and forward chaining. Some production rules use an additional control structure called pattern-matching [Durkin, 1994]. **Pattern-matching** is used when a rule is applied for a set of similar goals. To avoid writing a single rule for each goal, a general rule including variables is included. These variables can be matched to a specific set of values valid for the problem at hand. More detailed discussion about pattern-matching is described in the discussion about frame representation, as frame-based representations employ pattern-matching extensively. First, the two main control structures are described in more detail.

Backward chaining, also called goal directed reasoning, solves a design question by selecting a relation which can determine its value. However a relation can only be selected when its conditions are satisfied. If the relation or the condition(s) contain unknown parameter values, then these parameters are put on a so-called ‘goalstack’. For all these parameters a valid relation must be selected. This process is repeated until all parameters on the goalstack can be determined with valid relations.

Forward chaining, also called goal driven reasoning, starts with a known design parameter value. This parameter is used to evaluate the relations and the conditions which contain this parameter. Using this parameter value, one or more valid relations can solve unknown parameters. The new known parameter values are put on a so-called ‘forward stack’. This process is repeated until the top-goal is known or all parameters on the forward stack are used.

The contrast between forward and backward chaining has already been addressed by Lewis Carrol [1865] in his book “Alice in Wonderland”. The king and Alice seem to reason by forward chaining, while the queen demands reasoning by backward chaining:

"Let the jury consider their verdict", the King said.
"No, no!" said the Queen.  "Sentence first - verdict afterwards"
"Stuff and nonsense!" said Alice loudly.  "The idea of having the sentence first!" [Carrol, 1865]

A pure backward or forward chaining process is not efficient for searching the appropriate rules within a large set of rules, as pure backward chaining can cause data inconsistency and pure forward chaining can cause unnecessary search actions. By combining these processes a more efficient method, called 'bi-directional chaining', is acquired. Figure 7.2 shows this combination [de Swaan Arons, 1991].

Knowledge about forward- and backward chaining involves establishing goal-priorities when selecting the unknown goal on the goalstack or the known goal on the forward stack. This knowledge, also called meta-knowledge, determines how a design problem is solved. If meta-knowledge is not correctly used, the tool spends needless time asking questions while a simple and immediate conclusion could have been reached. Some examples of simple meta-rules are:
• Context limiting: prefer rule which contains similar knowledge as the last applied rule.
• Size ordering: prefer rule with most valid conditions
• Data ordering: prefer rule with least number of sub-goals
• Specificity ordering: prefer rule whose conditions are part of another rule
• Demons: prefer rule as soon as the conditions are valid

![Diagram of Forward & Backward reasoning](image)

Figure 7.2  Forward & Backward reasoning

Rule-based representations have been applied to many applications. A typical example of using a rule-based representation for conceptual container-ship design is described by [Welsh, 1990]. From this example and from literature the following advantages and limitations are learned.

**Advantages of rule-based representation**

• Rules are easy to encode because individual rules can be easily interpreted using conditional statements.
• The total set of rules is easily to expand, as they are implemented in an independent sequence.
• Relations are easily selected, as the bi-directional chaining control structure proposes valid relations, based on currently known parameters.

These advantages supports tool features 8, 13 and 16 which supports the designer respectively while representing numerical conditions, incremental programming and finding a valid set of relations.

**Limitations of rule-based representation**

• Rule-based representation requires exact matching. The conditions for an available rule must be fulfilled exactly by the current achieved goals. This requires strict coding of the rules, if the goal differs from the way the rule is coded, then its condition cannot be examined.
This disadvantage requires a high performance for tool feature 1 and 6, which code the mathematical parameters and relationships.

- Although individual rules can easily be interpreted, it is difficult to indicate the effect of a change through a complete network of relations.

This disadvantage requires a high performance for tool feature 20 and 21. The first feature performs the (re-) calculation of the rules due to a changed input value, the second feature explains the design how a solution is derived.

- The set of rules must be complete in order to solve a problem.

This disadvantage requires a high performance for tool feature 17, which handles errors due to incomplete knowledge.

Knowledge representation and reasoning by semantic networks

The knowledge representation by a semantic network is built from nodes and arcs, providing a graphical view of relations between properties of the design. The nodes in these networks correspond to the properties, while the arcs represent the relationships. Semantic nets can represent all kinds of relationships among the design properties, typical examples are: abstraction-, property- or component hierarchies [Dym, 1991], see figure 7.3. Semantic net representations are applied since the earliest attempts to represent knowledge. The figure shows an example of a semantic net showing two abstraction hierarchies (linked by shaded arrows) and a component hierarchy (linked by solid arrows).

![Semantic Network Diagram](image)

Figure 7.3  Abstraction, property and component hierarchy

**Abstraction hierarchy** represents levels of abstraction within the knowledge. The closer to the root of the hierarchy, the more general the knowledge about a property is described. Thus, what is known about a property at any level in the hierarchy will typically be valid for any level below it in the hierarchy. The relationship between two abstraction levels is generally termed ‘can be’ or ‘sub-category of’. At the deepest level of the abstraction hierarchy the knowledge about a property is called ‘instance’. An instance is a unique part of knowledge, representing a specific case about the more general knowledge one level above.

**Property hierarchy** represents the levels at which a value is assigned to a property within the abstraction hierarchy. The relationship between a property and a value is
generally termed 'has value' or 'value of'. As long as a value is not assigned to the
property, its value is defined as 'unknown'.

Component hierarchy represents the hierarchical breakdown of the physical component
described by the properties. The relationship between two component levels is generally
termed 'has part' or 'is part of'. In appendix A a collection of objects is introduced,
which represents a component hierarchy as applied in existing submarine designs.

Two main control structures are used to specify the reasoning process contained in a
semantic network: inheritance and exception handling.

Inheritance is a technique which enables lower level nodes to inherit automatically the
information of the nodes at a higher level within a hierarchy.

Exception handling is a technique which enables to correct general properties deeper
within the hierarchy. When a node inherits incorrect information, a new node is linked
to it that over-rides the inherited information. Exception is a simple technique used to
avoid problems within a semantic net.

From literature the following advantages and disadvantages are determined.

Advantages of semantic network representation

• The knowledge can be structured according to a component hierarchy.

This advantage supports Tool Feature 13, which requires incremental programming.
The component hierarchy divides the body of knowledge into modules, each containing
the knowledge about a component. Components can easily be added by linking them
to high level nodes currently in the network.

• The abstraction hierarchy enables inheritance of knowledge from an abstract
level to an application level.

This advantage supports tool feature 14, which requires multiple use of knowledge. The
abstraction hierarchy enables definition of general valid relations which can be applied
to determine parameter values for different conditions. Exception handling can be
applied if (a part of) the general relations must be replaced by a more specific relation.

Limitations of semantic network representation

• The semantic net representation shows all design knowledge by nodes and
arrows. They become chaotic and unmanageable when representing large
amounts of knowledge [Dym, 1991].

This disadvantage requires a high performance for tool feature 15, which presents the
structure between conditions, parameters and relations.

Knowledge representation and reasoning by frame hierarchies

The knowledge representation by frames is almost equal to the representation by
semantic networks, however the nodes are replaced by frames containing one or more
slots. Each slot encapsulates a design property or method. A method is defined as a set
of actions which are internally consistent and can be applied to solve a clearly defined
goal. Encapsulation of knowledge within methods keeps the details of frames neatly
within the frame, rather than spread around a series of rules or related nodes. This enhances maintenance and debugging of knowledge within the methods. However, the representation by methods also has a limitation when a large number of methods is required to solve a design problem. When something goes wrong, it is difficult to determine which method is the root of the problem. This may cause extensive debugging.

Table 7.1 shows an example of these slots. The first slot is usually the name of the frame. Besides the property characteristics a slot can also contain a method. The slots may be filled with known values or they may be empty. Empty slots have the value ‘unknown’. Each frame also contains control knowledge which represent expectations for its use within the design process. For example, to each frame all other frames are known to which it is connected.

<table>
<thead>
<tr>
<th>Name</th>
<th>Unique name for reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>legal range of values</td>
</tr>
<tr>
<td>Conditions</td>
<td>A set of conditions which have to be checked before a value is estimated</td>
</tr>
<tr>
<td>Checks</td>
<td>A set of checks which should be checked before a value is accepted</td>
</tr>
<tr>
<td>Value</td>
<td>Represents the latest estimated value</td>
</tr>
<tr>
<td>Unit</td>
<td>Unit which refers to the current value</td>
</tr>
</tbody>
</table>

Three control structures are used to specify the reasoning process contained in a frame-based representation: inheritance, message passing and pattern matching.

*Frame inheritance* causes the instance frame to inherit all the information from its higher level frame. Using this inheritance structure, related information, such as methods, can be used repeatedly without the need to develop repetitive blocks of data. If the information from the higher level is not valid, the information is over-ruled using exception handling.

*Message passing* is a technique which enables a frame to signal a message to another frame, which responds by executing a selected method. The method must thus be executed whenever requested. Using this technique enables frames at a high level to control the reasoning, without requiring the detailed information within the methods.

*Pattern matching* is a technique which scans the frames in the network to find a match. Operations are possible on knowledge in the frames which fits the match. Pattern matching is used to define an operation which is applied to all matching frames in the network.

Knowledge about the reasoning process, stored in a frame’s slot, can support the selection of useful operations. Examples of this kind of meta-knowledge are *Facets* [Durkin, 1994]. Facets are used to define initial property values, property’s type or limit possible values. They can also be used to define messages if a property value is needed, or if a value is changed.
Frame-based representations are more general to apply than semantic networks. An example of a frame-based representation used in ship design is the ‘Intelligent Design Engineering system based on network Analysis’ by [Akagi, 1991]. The abstraction hierarchy is used to represent the ship design knowledge by a hierarchy of design methods. At each level a method can determine a value of a design property. If property values are requested as input for a selected method, then messages are passed. These messages can contain either a request for a value provided by the designer, or a selection of a method defined one level deeper within the abstraction hierarchy. The example also shows a component hierarchy, which is used to represent groups of physical components, such as Hull Steel, Machinery-Part and Outfit [Akagi, 1991].

![Diagram of frame-based representation](image)

**Figure 7.4  Frame based representation**

From this example and literature the following advantages and limitations are determined.

**Advantages of frame-based representation**

- Encapsulation of knowledge within methods keeps the details of frames neatly within the frame.
  This advantage supports Tool Features 1 to 9, which require facilities for coding relevant characteristics of parameters, relations and conditions.
- The body of knowledge can easily be maintained, by adding or removing frames.
  This advantage supports Tool Feature 13, which requires incremental programming. All relevant information about parameters and relationships are stored in frames, which can easily be added, modified or deleted.
- Using the abstract hierarchy of frames slot values or methods can be inherited from frames higher in the hierarchy.
  This advantage supports Tool Feature 14, which requires multiple use of knowledge.
Limitations of frame-based network representation

- While debugging the message passing process, it is difficult to trace the location in which something goes wrong.

This disadvantage requires a high performance for Tool Features 17 and 21. The first feature supports the detection of an error, and the second explains how the knowledge is applied.

Identifying candidate knowledge-based tools

The candidate tool requires hybrid representation and reasoning techniques. Knowledge-based tools possessing these techniques can originate from shells that can be applied to - at least in principle - any type of application, or from shells oriented towards a specific application. Development through a shell which includes more specific representation and reasoning techniques, is much faster than by means of more general-purpose shell. The price paid for the higher level of support is the lower level of flexibility. Small mismatches between on the one hand the required representation and reasoning techniques and on the other hand the available representation and reasoning techniques in the tool, have to be supported by a variety of external applications.

To support prototyping, a suitable shell has to be selected. Guida [1994] presents a list of commercially available shells. However, the rapid evaluation of these products makes any attempt for reviewing the features, strengths and weaknesses outdated. Moreover, any candidate shell will have to be adjusted before it can employ the desired hybrid representation and reasoning techniques as described. In 1993 two promising application specific shells have been examined, which fulfill most of the tool features 1 to 20 and which are powerful enough for practical-size models [vd Nat, 1993b]:

- DESIGNER, developed by University of Strathclyde, Glasgow - Scotland [MacCallum, 1982;1985;1987;1989;1990;1993]

When comparing these tools the major differences are found in the reasoning techniques. Table 7.2 shows these differences [vd Nat, 1993b]. Note that the complete functionality of the tool is not presented. The description is restricted to the main features, considering the applied reasoning techniques.

The knowledge-based tool QUAESTOR possesses more promising techniques for reasoning with submarine design knowledge than DESIGNER. This is motivated by the observations in table 7.2:

- The problem in DESIGNER is defined, assuming all independent parameter values are known, whereas the submarine designer defines values for independent parameters based on available intermediate results.
- Forward reasoning in DESIGNER is applied for updating values. The mechanism has not been applied for finding relationships with only one unknown parameter value, which enables minimizing the required input values.
• The meta-knowledge applied by DESIGNER requires knowledge about numerical empiricalism in the design (for example reliability of relations). For submarine design this knowledge is not available.
• The numerical models which are applied in submarine design require a directed network in which strong components occur frequently. Strong components cannot be handled by DESIGNER.

<table>
<thead>
<tr>
<th>Problem definition</th>
<th>DESIGNER</th>
<th>QUAESTOR 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Goal search: specification of one or more input parameters which can be altered by DESIGNER to produce a required value for a specific parameter</td>
<td>Goal determination: find valid relationships for one or more (sub-) goals and if not available ask input value</td>
</tr>
<tr>
<td>Reasoning mechanism</td>
<td>Backward reasoning and forward consistency checking</td>
<td>Bi-directional reasoning</td>
</tr>
<tr>
<td>Meta-knowledge</td>
<td>Priority within selection is based on level of uncertainty</td>
<td>Priority within selection is based on 'naval architect' heuristics</td>
</tr>
<tr>
<td>Solution</td>
<td>Directed network of relationships, free from strong components</td>
<td>Directed network of relationships, in which all strong components are solved simultaneously</td>
</tr>
</tbody>
</table>

Although the knowledge-based tool QUAESTOR 1.0 [van Hees, 1991] possessed promising techniques, it had not reached the stage where it can actually be used for solving practical submarine design problems of a realistic size.

To support the development of QUAESTOR a number of proposals were made for improving this tool [vd Nat, 1993a]. The most important proposals are summarised in table 7.3. The result of the development is a second version of QUAESTOR [van Hees, 1993]. The second version of QUAESTOR is chosen as the tool for SUBCEM.

<table>
<thead>
<tr>
<th>TF</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Adding database and database operations</td>
</tr>
<tr>
<td>13</td>
<td>Subdivision of knowledge into classes</td>
</tr>
<tr>
<td>14</td>
<td>Enabling multiple use, defined by special operation</td>
</tr>
<tr>
<td>15</td>
<td>Listing relationships and parameters</td>
</tr>
<tr>
<td>20</td>
<td>Solving each individual strong component</td>
</tr>
<tr>
<td>22</td>
<td>Adding strategic explanation</td>
</tr>
</tbody>
</table>
Many improvements are made during the development of QUAESTOR. However, still a few TF’s are not implemented at the end of the development of the second version of QUAESTOR. Table 7.4 shows a summary of these not implemented tool features.

<table>
<thead>
<tr>
<th>TF</th>
<th>Part of TF which is not implemented</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Types mathematical parameters</td>
</tr>
<tr>
<td></td>
<td>Other types different from double precision</td>
</tr>
<tr>
<td>10</td>
<td>Unit check</td>
</tr>
<tr>
<td>11</td>
<td>Mathematical relationships</td>
</tr>
<tr>
<td></td>
<td>More advanced algebraic operations like differentiating or integrating</td>
</tr>
<tr>
<td>14</td>
<td>Multiple use of knowledge</td>
</tr>
<tr>
<td></td>
<td>Storage and presentation of Intermediate results of multiple used knowledge</td>
</tr>
<tr>
<td>16</td>
<td>Directing undirected network</td>
</tr>
<tr>
<td></td>
<td>Priority definition by knowledge engineer</td>
</tr>
<tr>
<td>17</td>
<td>Detection inconsistencies</td>
</tr>
<tr>
<td></td>
<td>Detection and presentation of the redundant rules during the search process</td>
</tr>
<tr>
<td>18</td>
<td>Solving implicit relationships</td>
</tr>
<tr>
<td></td>
<td>Other methods different from Newton-Raphson or a modified version of this method</td>
</tr>
<tr>
<td>19</td>
<td>Optimisation</td>
</tr>
<tr>
<td></td>
<td>Optimisation of a single goal parameter within a strong component</td>
</tr>
<tr>
<td>21</td>
<td>Explanation facilities</td>
</tr>
<tr>
<td></td>
<td>Adding strategic explanation</td>
</tr>
</tbody>
</table>

Table 7.4 Not implemented Tool Features in QUAESTOR 2.0

Figure 7.5 shows the global architecture of the knowledge-based tool QUAESTOR 2.0.

![Diagram of the global tool architecture of Knowledge-Based tools](image)

Figure 7.5 Global tool architecture of Knowledge-Based tools

The Knowledge base stores the available design knowledge in an appropriate explicit form, which can be used by an inference engine. Through ‘procedure calls’ used in the design knowledge, external applications can be integrated with the tool. Database
operations can exchange data with databases. The Inference engine contains a reasoning mechanism to draw conclusions about a problem, by matching facts contained in a work base with design knowledge in the knowledge base. The way of reasoning is explained by an explanation facility. The Work base contains the problem facts that are discovered during the solving process. The figure also shows two users: a knowledge engineer and a designer. The two types of users represent the separation between the implemented knowledge by the knowledge engineer and the usage of this knowledge by the designer.

The Knowledge-base of QUAESTOR 2.0
The knowledge base of this tool contains mathematical models and relevant information about the way these models are used in practical applications, the so-called control knowledge. The mathematical models are formalised abstractions of design concepts, using parameters, relations and constraints. Table 7.5 shows their characteristics.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>RELATION</th>
<th>CONSTRAINT</th>
</tr>
</thead>
<tbody>
<tr>
<td>name</td>
<td>accept by user/tool</td>
<td>accept by user/tool</td>
</tr>
<tr>
<td>initial value</td>
<td>use as function/equation</td>
<td>show use</td>
</tr>
<tr>
<td>input expected by user/tool</td>
<td>allow use if all/one</td>
<td>reverse logic</td>
</tr>
<tr>
<td>valid value range</td>
<td>constraint(s) true/false</td>
<td>explanation, background data</td>
</tr>
<tr>
<td>unit</td>
<td>physical/empirical</td>
<td>numerical data</td>
</tr>
<tr>
<td>value</td>
<td>explanation, background data</td>
<td></td>
</tr>
<tr>
<td>related</td>
<td></td>
<td></td>
</tr>
<tr>
<td>explanation, background data</td>
<td>numerical data</td>
<td></td>
</tr>
<tr>
<td>numerical data</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PARAMETER
Name parameter - Each parameter has a unique label, containing the name of the parameter.
Initial value - The initial value contains a parameter value which has the same magnitude as expected solution. This value is used within the first step of an iterative method, which solves the strong component which includes the parameter.
Input expected by user or by tool - The parameter value can either be provided by the designer and/or calculated by a relation.
Valid value range - The value of the parameter can be limited to a valid value range.
Unit - Each parameter expressing a physical property has a unit to express the magnitude of the value.
Value - Value contains the actual value of the parameter, which can either be an initial/undervived or a derived value.
Related parameter - If parameters are 'related', each of these related parameters is presented once to the designer for an input value. As the parameters are related by
control knowledge they don’t have to be related by relations. The related parameters express an expected dependency between the parameters. This expected dependency may support the reasoning process, as the designer can give input values to a few parameters which are all related.

**Explanation, background data** - To explain the name, purpose and origin of the parameter a reference text is applied. If the parameter value can be provided by the user, an appropriate value is presented.

**Numerical data** - The parameter can contain one or more sets of parameter values, which are part of a database.

**RELATION**

**Accept relation only by user (soft-relation) or always by tool (hard-relation)** - A parameter value calculated by relationships may have a number of valid relationships for estimating a value. The choice of the relationship to be used can be made explicitly by the user or by the tool.

**Use relation as a function or as an equation** - The equal to, ’=’, sign in a relationship represents the dependence between the parameters within the relationship. If the relationship is a 'function', the equal sign implies a direction in the dependency. If the inverse of the dependency is valid too, the relationship is called an 'equation'.

**Allow use of relation if all or only one constraint is valid** - A relation is only allowed to be applied when its constraint(s) are valid, this can either be one or all its constraints.

**Physical/empirical relation** - The origin of the relation can either be based on physical or on empirical information. Two empirical relations which can determine the same parameter, cannot both be applied for solving a problem. Physical relations do not have this restriction.

**Explanation, background data of relation** - To explain the purpose, origin and restrictions of the relation a reference text is applied.

**Numerical data of relation** - A relation can contain one or more functions which require a set of values. For example for the polynomial functions the values of the polynomial coefficients and for the interpolation functions the data pairs.

**CONSTRAINT**

**Accept constraint by user or by tool** - A relationship may have a number of valid constraint(s). The choice of which constraint(s) will be applied can be made explicitly by the user or by the tool.

**Show use of constraint** - If the constraint is not valid, a message is passed to the user.

**Reverse logic of constraint** - The constraint becomes valid when its logical expression is not valid.

**Explanation, background data of a constraint** - To explain the purpose and origin of the constraint a reference text is applied. If the constraint can be shown to the user, a proposal for a correction is added.

**Numerical data of a constraint** - A constraint can contain one or more functions which require a set of values.
Almost all numerical knowledge is implemented in the knowledge base of QUAESTOR. Two exceptions are made:
- Models which contain a optimisation procedure
- Models which contain only deep knowledge and which are only applied in one way

The first exception must be made as QUAESTOR cannot optimise a single goal in a strong component. The second exception should be made as it is expected that models which contain only deep knowledge do not change much in future.

Table 7.6 shows which models are implemented in the knowledge-based tool:

<table>
<thead>
<tr>
<th>Function</th>
<th>Sizing model</th>
<th>Performance model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrying platform</td>
<td>space</td>
<td>weight</td>
</tr>
<tr>
<td>Manoeuvring</td>
<td>QUAESTOR</td>
<td>QUAESTOR</td>
</tr>
<tr>
<td>Energy supply</td>
<td>QUAESTOR</td>
<td>QUAESTOR</td>
</tr>
<tr>
<td>Life support</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Special functions</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Inference engine of QUAESTOR 2.0
The inference engine of this tool supports the user with the configuration of the mathematical model also called template. The mathematical model represents a valid path through the network of relevant model fragments from input to output parameters. A key principle for the inference engine is that each unknown parameter introduces only one relation in the template. Each introduction is recorded in two ways: each parameter chains to a relation and each relation chains to one or more parameters. This recording enables a full history of inference which is used to keep the output values always consistent with the input values.

To introduce a relation, the tool selects from the knowledge base all valid, non-used and non-rejected relations which can derive the parameter value. If more than one relation is available, a priority is made by applying so-called heuristic rules. Heuristic rules contain information about how design knowledge should be applied, e.g. 'relation with only satisfied constraints has higher priority than relation with pending constraints'. Note that the status of a constraint can be 'satisfied', 'pending', or 'not satisfied'. When all the constraints of a relation are satisfied, it is valid to use the relation for solving the problem. When the status of a constraint is 'pending' not enough knowledge is currently available for determining whether the relation is valid or not valid. This heuristic and other heuristics are explained in some detail by Westen [1991] and Van Hees [1997].
When a relation has the characteristic ‘accept by user’, it is first proposed to the designer, before introduction is possible. This user-driven process is continued until all unknown parameters introduce a valid relation, in other words a complete template is inferred. This template is manipulated symbolically in order to reduce degrees of freedom. Subsequently, it is solved by means of a non-linear, multi-dimensional Newton-Raphson method. The convergence criterion between two successively obtained solutions is checked at three sequential levels [van Hees, 1997]. Table 7.7 shows when convergence is achieved for each of the three levels.

<table>
<thead>
<tr>
<th>Level</th>
<th>Involves</th>
<th>Criterion value</th>
<th>Convergence is achieved:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>All parameters in strong component and solver accuracy value</td>
<td>Sum of the absolute initial values of all parameters in the strong component, multiplied by the solver accuracy value</td>
<td>Difference between the sums of the absolute parameter values in the strong component of two successive solutions is less than the criterion value</td>
</tr>
<tr>
<td>2</td>
<td>Each individual parameter value and the solver accuracy value</td>
<td>Solver accuracy value</td>
<td>Absolute value of the ratio between two successive parameter values is within the criterion value from unity</td>
</tr>
<tr>
<td>3</td>
<td>Control knowledge of the parameter</td>
<td>Valid value range of the parameter</td>
<td>Current solution is not in conflict with criterion value</td>
</tr>
</tbody>
</table>

If the results are valid, i.e. if all constraints imposed on the relations in the template are fulfilled, the problem is solved. If one or more results are not valid, the template has to be changed by applying other relations, if possible. The selection of valid relationships moves the problem from simple numerical evaluation into a complex conditional evaluation.

Some problems can not be solved as the wrong relation is selected for the calculation of a specific characteristic. For example, problems become unsolvable by insufficient data when only one relation is applicable to solve a characteristic, but the relation cannot be applied as it has been chained, earlier in the design process, to another characteristic. Despite another relation is being available to solve this earlier chained characteristic, the tool will not unchain the relations to allow the selection of the other available relation for the earlier chained characteristic. To overcome this issue, the designer has to be aware and must select the proper soft-relation. The knowledge engineer can overcome this issue by assigning constraints to the relations. During the design process only the correct relations are valid. However, constraints limit the entropy of the design knowledge.

The Work base of QUAESTOR 2.0
The work base of this tool contains the design problem, input parameter values and (intermediate) results of the calculations. The design problem is defined by requesting
the value of one or more unknown parameters in the knowledge base. After solving a problem it is possible to recalculate the problem with other input values, to change the problem or even to reverse the original problem. A solvable template with input can be stored in the knowledge base as a 'macro' for re-use.

**Explanation facility of QUAESTOR 2.0**
The explanation facilities of this tool show to the designer the strategy that was followed to create the model. A tree structure is used to visualise the steps taken in this strategy.

**Interface of QUAESTOR 2.0**
Two types of interfaces are distinguished: Human interface and tool-to-tool interface.

The human interface between the user and the tool is divided in two main parts: interface between knowledge engineer and knowledge base and the interface between designer and inference engine - work base - explanation facility. The knowledge engineer acquires valid mathematical relations and formalises their representation in the knowledge base. The designer configures models for arbitrary problems in dialogue with the tool. Both the knowledge engineer and the designer have access to all implemented knowledge.

The tool-to-tool interface gives commands to external applications (procedure-based tools) any time QUAESTOR selects a relation or constraint which contains a call to the specified application. To communicate to these applications a protocol is defined. This protocol uses ASCII files containing single and/or multiple parameter value combinations in a so-called TExt-LIst-TABle format [van Hees, 1997].

**Database of QUAESTOR 2.0**
The database of the tool contains records of parameter values stored at the associated parameter.

**7.2.2 Procedure-based tools**
A procedure-based tool is a software tool which has two characteristic capabilities: first, supporting the representation of knowledge about a specific application and second, exploiting the knowledge through fixed algorithms. Typical for procedure-based tools is the fusion of these two capabilities. This fusion gives these tools the advantage of high computational efficiency when a known fixed solution algorithm can be applied. However, fusion also implies a disadvantage, as changes made in the algorithm requires understanding and changing the procedural program code.

**Identifying candidate procedure-based tools**
The candidate tool requires spatial representation and calculation techniques to fulfill Tool Features 19 and 23 to 28.

The optimisation of a single goal parameter is applied in the sizing model of the primary structure and in the sizing model of the propeller. Only tailor made tools can
provide the facilities to implement these models. The primary structure sizing model is implemented in the tool called “SUBMARIN” [Groen, 1996]. The propeller sizing model is implemented in the tool called “SUBPROP” [vd Nat, 1996d].

The geometrical and topological space properties are specific for submarines, therefore only a tailor made tool can provide the facilities to fulfill the required tool features. This tool is called “SUBSPACE” [van Duuren, 1993-1995]. SUBSPACE has two major functions. The first function is to enable the designer to generate an internal arrangement of spaces and allocation of objects to these spaces. The second function is to evaluate the feasibility of the defined arrangement.

The global working of SUBSPACE is as follows. The designer specifies a concept tree to generate an arrangement of spaces and objects. This tree is applied to display the sequence of spaces and objects in the concept. The sequence of spaces and objects defines a relative position. Figure 7.6 shows a part of such tree, with below the represented submarine.

![SUBSPACE concept tree]

Within the tree representation the sequences have the following meaning:

- Sequence of compartments represents the sequence of location from aft to front.
- Sequence of cells represents the sequence of location from top to bottom.
- Sequence of appendages, added hulls and outer hull represents the priority of the spaces. Overlapping space belongs to the space with a higher priority.
- Sequence of objects represents the sequence of allocation.
To avoid inconsistencies in the arrangement, after each action of the designer, the tool evaluates the feasibility. This enables the designer to apply his experience and skills when specifying an internal arrangement. The space-sizing algorithm, as presented in chapter six, is applied to re-calculate space properties, such as package efficiencies. The efficiencies inform the designer instantly about the effects of different layouts on the feasibility of a design proposal.

The knowledge-based tool is able to communicate with the procedure-based applications, according to Tool Feature 12. When during the reasoning process any of the functions within SUBSPACE is required, the knowledge-based tool prepares an input communication file, runs the application and finally retrieves one or more parameters from the application’s output communication file. SUBSPACE contains several applications each having one or a number of specific functions. Table 7.8 summarises these functions. A detailed description of these functions is given by vd Nat [1996c].

<table>
<thead>
<tr>
<th>Program</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>DELEPI</td>
<td>Clear communication from previous design actions by deleting all</td>
</tr>
<tr>
<td></td>
<td>communication files with knowledge-based tool</td>
</tr>
<tr>
<td>INITCONC</td>
<td>Initialise the current concept data files</td>
</tr>
<tr>
<td>INITVAR</td>
<td>Initialise the current concept variant data files</td>
</tr>
<tr>
<td>DEFOBJ</td>
<td>Transfer the object data from knowledge-based tool to SUBSPACE</td>
</tr>
<tr>
<td>ASOBTOPS</td>
<td>Define inboard or outboard concept and allocate objects to spaces</td>
</tr>
<tr>
<td>MASSPRIM</td>
<td>Determine the mass of the primary structure (using SUBMARIN)</td>
</tr>
<tr>
<td>SECSTRUC</td>
<td>Determine the mass of the secondary inboard or outboard structure</td>
</tr>
<tr>
<td>CALCOH</td>
<td>Determine the critical cross section in the primary structure for the outer</td>
</tr>
<tr>
<td></td>
<td>hull both in the front and aft section of the boat</td>
</tr>
<tr>
<td>SHOWBOAT</td>
<td>Show the longitudinal cross section of the inboard and outboard spaces</td>
</tr>
<tr>
<td>SHOWSTAB</td>
<td>Determine the static stability in submerged and surfaced condition</td>
</tr>
<tr>
<td>DCONTROL</td>
<td>Transfer data from knowledge-based tool to SUBSPACE or in reverse</td>
</tr>
<tr>
<td></td>
<td>direction</td>
</tr>
</tbody>
</table>

The SUBSPACE applications all use an external concept data base, in which the geometric and topologic data are stored. To maintain consistency between this data and the data in the work base of the knowledge-based tool, two coding standards are recommended:

- Delete all communication files before a reasoning process starts.
- Use date-time parameter value in communication between knowledge-based and procedure-based tool.

122
As a first coding standard it is recommended to prevent an application being executed when its communication input file is equal to the input file used in the previous reasoning process, while its data from the external database is not equal. As a second coding standard it is recommended to determine whether the results from a procedure-based application are valid or outdated.

7.3 Quality control of the prototype

Quality control is of primary importance for successful use of software. The process of quality control specifies the quality control actions relevant to the development process and the product. In this project the product is an implemented concept exploration model (CEM). Quality is measured by two actions: first, comparing the desired CEM capabilities to its specifications and second, comparing the CEM specifications to its implementation. Both actions are described for the knowledge-based tool in a quality control plan [vd Nat, 1995]. To control the quality, it is important that this plan spans all tasks performed during the entire life cycle of the application, starting from the first coding. Appendix B and C give an example of the manner in which the quality control plan is applied.

7.4 Conclusions

From the body of knowledge in chapter six a large number of tool features are formulated to support the implementation of this body of knowledge. A combination of knowledge-based and procedure-based techniques showed the most promising method for implementing the body of knowledge. When using these tools for exploration of design problems, the inference engine of the knowledge-based tool controls the selection of the knowledge.

From examined knowledge-based tools in 1993, the tool QUAESTOR supported most of the tool features. During the research project a second version of this tool became available, including almost all the desired Tool Features. No procedure-based tool supported the formulated tool features. A tailor made tool, called SUBSPACE has been developed to include all the desired tool features. Using the tools QUAESTOR and SUBSPACE/SUBMARIN/SUBPROP, all models formulated in chapter six can be implemented. Due to restricted research resources, a number of models could not (yet) be implemented. Table 7.9 shows the models which are actually implemented.

To apply the implemented knowledge successfully, quality control during the entire development process appeared essential. This is especially true when the amount of implemented knowledge became substantial.
<table>
<thead>
<tr>
<th>Function</th>
<th>Sizing model space</th>
<th>Sizing model weight</th>
<th>Sizing model energy</th>
<th>Performance model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrying platform</td>
<td>SUBSPACE</td>
<td>SUBSPACE SUBMARIN</td>
<td>QUAESTOR</td>
<td>SUBSPACE</td>
</tr>
<tr>
<td>Manoeuvring</td>
<td>QUAESTOR</td>
<td>QUAESTOR</td>
<td>QUAESTOR SUBPROP</td>
<td>QUAESTOR</td>
</tr>
<tr>
<td>Energy supply</td>
<td>QUAESTOR</td>
<td>QUAESTOR</td>
<td>QUAESTOR</td>
<td>QUAESTOR</td>
</tr>
<tr>
<td>Ship management</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Navigation and Observation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication</td>
<td></td>
<td></td>
<td>QUAESTOR</td>
<td></td>
</tr>
<tr>
<td>Life support</td>
<td></td>
<td></td>
<td></td>
<td>QUAESTOR</td>
</tr>
<tr>
<td>Special functions</td>
<td></td>
<td></td>
<td></td>
<td>QUAESTOR</td>
</tr>
</tbody>
</table>

Note: blank cell means a model is not (yet) available/implemented
USABILITY OF CONCEPT EXPLORATION MODEL

Concept studies will rarely define a solution but most prove that a solution is possible
D.K. Brown

In order to establish how SUBCEM might be applied to the design of submarines, it is necessary to evaluate the usability of the implemented model. The goal of this evaluation is to show the robustness of the models and efficiency of the solving process. Case studies are performed to show examples of questions which can be solved. An important case study involves the design of an existing submarine. Beside the case study, a number of parametric studies are performed to demonstrate the capability of re-design. Different parametric variations are performed, based on submarine design questions which have been reported in literature e.g. [Jackson, 1992]. The effort required to perform these studies is evaluated to rate the efficiency of the tool.

The first part of this chapter presents the case studies and evaluates the usability from the knowledge engineer's point of view. This part describes case studies which evaluate the conceptual design process of a submarine of about 3000 [ton] submerged displacement. The evaluation includes a complete design session to show how the design tasks are performed and it includes a number of parametric studies to show the effect of changing equipment and/or layout on the performance of the boat. As information on the design of submarines is partially confidential on account of the military security classification, not all details on in- and output data can be given. Still, these test cases give an impression of the capabilities of the tool.

The second part presents the opinion of designers. For example the relevance of the design questions and the effort to solve these questions is evaluated. Designers should be involved in the development and evaluation of these systems. As only they can identify the potential improvement of efficiency which can be achieved by using such a system.
8.1 Concept design case

The main design task is to create a design description which fulfills all client's formulated requirements. The first case study includes a 'run through', to show how this task is performed. On starting up the system, the initial dialogue allows the user to define one or more questions about the concept. These questions can be about for example the size of equipment, the amount and location of ballast, or the submerged range. However, usually a sequence of questions is defined by the user using a bottom-up design strategy. Typically, the questions are related to the sequence of the design tasks which have to be performed. The bottom-up strategy starts with questions about sizing the components and the boat, followed by questions about balancing the boat and at last questions about the performance characteristics of the submarine. If the performance characteristics are not correct, the design process is repeated until the performance meet the client's requirements. The amount of information that is asked for and consequently the amount of output produced by the system is too great to be fully covered. Therefore only the most interesting aspects and data will be described. The 'run through' case specifies the operating condition and input values of an existing submarine. During the case study intermediate results are discussed, especially whether they are equal or not to the expected outcomes (robustness). The results of the test case are used in the next sub-paragraph as a starting point for the parametric studies.

Within SUBCEM, each design task is marked in time to specify the last moment a specific design task has been performed. When the designer specifies a new design task, the system recognises the design tasks which must be performed in advance and will thereby maintain the results of the different design tasks consistent. Using this sequence of design tasks, the system performs all the design tasks which are necessary before a requested design task can be performed. In this way, for example, the question about the submerged range can only be solved when the system has performed the design task of sizing and balancing. Thus questions about the size of equipment and location of ballast will be raised by the system.

Table 8.1 shows the sequence of design tasks as defined by the user in this 'run through' example. Note that this sequence is chosen, but the tool allows any other sequence of design tasks. The first design task (1) involves the administrative task to determine whether the data of an existing, or a new concept are applied. The following six design tasks define and size equipment, spaces and structure of the concept. After sizing all inboard objects (2), the layout of the inboard spaces is defined and sized (3). By allocating objects to these spaces, length, area and volume become occupied. As the space sizing algorithm does not allow an object to be allocated to any spaces in which the free space is not sufficient, the space balance is achieved continuously during the allocation of objects to spaces. After realisation of the inboard concept, the inboard primary and secondary structure is sized (4). All inboard design tasks are also performed for the outboard concept (5, 6 and 7). Not all properties of all objects can be sized as they were dependent on the properties of the concept requirements, for
example the size of the propulsor depends on the propulsion performance since the hydrodynamic resistance depends on the speed and the size of the boat. Thus before the weight can be balanced, first the performance parameters for propulsion are calculated (8) and the results are applied to size the supplementary objects (9). After sizing all the equipment and spaces, the next task (10) is to balance the weight of the concept by adjusting the ballast. Finally in this "run through" the performance parameters for stability (11) and energy supply (12) of the concept are calculated. Note that all presented results are calculated values.

Table 8.1 Examples of main design tasks

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Concept identification</td>
</tr>
<tr>
<td>2</td>
<td>Definition and sizing inboard objects</td>
</tr>
<tr>
<td>3</td>
<td>Definition and sizing inboard concept (layout of spaces and allocation of objects)</td>
</tr>
<tr>
<td>4</td>
<td>Definition and sizing inboard primary and secondary structure</td>
</tr>
<tr>
<td>5</td>
<td>Definition and sizing outboard objects</td>
</tr>
<tr>
<td>6</td>
<td>Definition and sizing outboard concept (layout of spaces and allocation of objects)</td>
</tr>
<tr>
<td>7</td>
<td>Definition and sizing outboard secondary structure</td>
</tr>
<tr>
<td>8</td>
<td>Determination propulsion performance</td>
</tr>
<tr>
<td>9</td>
<td>Sizing supplementary objects (object properties depending on the resulting boat design)</td>
</tr>
<tr>
<td>10</td>
<td>Determination weight balance (required fixed and variable ballast)</td>
</tr>
<tr>
<td>11</td>
<td>Determination hydrostatic stability performance</td>
</tr>
<tr>
<td>12</td>
<td>Determination energy supply performance</td>
</tr>
</tbody>
</table>

* if performance is not correct, go back to task 2

Figure 8.1 shows the sequence of task graphically. Note that the space- and energy balancing tasks are performed in parallel of the sizing process of the objects and the concept. The result is a space- and energy driven design.

Figure 8.1 Main tasks in the 'run through' case
Each of the main design tasks is discussed in more detail.

8.1.1 Concept identification
Each concept must be identified in both the knowledge-based system QUAESTOR and the procedure-based system SUBSPACE. The procedure-based system identifies the concept by a unique concept number and unique concept variation number, which must be known within both systems. A concept can be defined as new concept, an existing or as a copy of an existing concept (variation).

8.1.2 Define and size inboard objects
Objects which may become part of the concept must be defined and its space, weight and energy properties must be sized. All defined and sized objects are collected in a list of ‘to be allocated objects’.

Objects are defined in the knowledge base by a unique object number. Some objects must be divided into several separate sub-objects, each adding to the object number a unique sequence number. Division of objects can be caused by:

- Allocation to different spaces, for example in- and outboard propulsion transmission (shafting).
- Different space and/or weight property values, for example different z-centroids of the main battery system.

However, division of objects should be avoided as the maximum number of allocated objects, which can be handled by SUBSPACE, is less than 100 objects. To model relative large components within the main electric room, engine room and diesel generator room of the 3000 [ton] submerged displacement submarine about 35 objects are sufficient. A component is defined as ‘relatively large’ when it is common practice to be drawn on a 1:50 scale general arrangement drawing (approximately the smallest size is larger than 0.5 [m]). For example, these drawings include trim/weight compensation pumps, but do not include piping or cables. Relatively small components are not modelled individually, but can be allocated as a distributed object. About 13% of all structural mass is allocated as distributed object and about 6% of all equipment mass is allocated as distributed object. Appendix A shows a list of all components, which are modelled as separate objects. Within this list distinction is made between objects of which properties are determined by models, or of which properties have constant (default) values, or which property values are combined with other objects.

A note must be made for the object ‘fluids ship handling’, which contains the variable ballast (weight compensation and trim tanks). Initially, the mass property of this object has no value, only the space properties are determined and represent the maximum available volume for variable mass. The amount of variable mass is determined during the performance calculations when the hydrostatic stability performance is calculated.

As an example of the object space and weight sizing models, the results of the space and weight models of the inboard component fulfilling the Propulsion driving function
is presented. The object properties are requested by asking the Main Electric Motor sizing task. Appendix B shows the input from the user, input from the knowledge base, and the derived values. The user can either be the designer of the component or the designer of the boat. Table 8.2 shows the input values with a high manipulative ability given by the designer of the boat (in bold), and the input parameter values which are usually only changed by the designer of the electric motor. The quantity of knowledge used in the main electric motor sizing model seems to be high, however this is justified by the high quality of the model which enables the calculation of the object properties for a wide range of performance values. The input from the knowledge base is implemented by the knowledge engineer and contains parameters with a low manipulative ability, but high discriminative ability. Most of these parameters represent technological constants.

<table>
<thead>
<tr>
<th>Table 8.2</th>
<th>Input and derived values of MEM sizing model</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DefMem</td>
<td>Last point of time DEFinition MEM</td>
<td>?</td>
</tr>
<tr>
<td>Discrete Input from Operator</td>
<td>(incl. from knowledge base)</td>
<td></td>
</tr>
<tr>
<td>B5Cont</td>
<td>Airgap induction (B5) in CONTinuous condition</td>
<td>0.75</td>
</tr>
<tr>
<td>B5Max</td>
<td>Airgap induction (B5) MAXimum allowable</td>
<td>1.08</td>
</tr>
<tr>
<td>Dhatch</td>
<td>Diameter of HATCH for maintenance purposes</td>
<td>0.9</td>
</tr>
<tr>
<td>HeatLoss</td>
<td>HEAT LOSS of MEM to mem room</td>
<td>5</td>
</tr>
<tr>
<td>Hshock</td>
<td>Height required for SHOCK</td>
<td>0.05</td>
</tr>
<tr>
<td>HiHcoolM</td>
<td>Ratio between actual height cooler at front</td>
<td>0.75</td>
</tr>
<tr>
<td>I0</td>
<td>Maximum [I0] current mem armature</td>
<td>3200</td>
</tr>
<tr>
<td>IshuntMa</td>
<td>Current [I] through shunt windings MAXimum</td>
<td>60</td>
</tr>
<tr>
<td>Jc</td>
<td>Maximum current density at max. cont.</td>
<td>586</td>
</tr>
<tr>
<td>JserieCo</td>
<td>Current density (J) of serie windings CORRECT-</td>
<td>0.91</td>
</tr>
<tr>
<td>JshuntCo</td>
<td>Current density (J) SHUNT windings CORREction-</td>
<td>0.66</td>
</tr>
<tr>
<td>Jw</td>
<td>Winding current density at max. cont. cond/[Am2]</td>
<td>356</td>
</tr>
<tr>
<td>KCUA</td>
<td>(KCU) Armature winding space factor</td>
<td></td>
</tr>
<tr>
<td>LShftInb</td>
<td>Length SHEFT inboard</td>
<td>4.34</td>
</tr>
<tr>
<td>MfoudnM</td>
<td>Ratio Mass FOUNDation and Mass MEM</td>
<td>0.1</td>
</tr>
<tr>
<td>Mth</td>
<td>Mcu</td>
<td>Ratio between Mass Thermal and Mass copper</td>
</tr>
<tr>
<td>NRevBurs</td>
<td>Number of REVolutions for BURSt speed</td>
<td>200</td>
</tr>
<tr>
<td>PhMemBur</td>
<td>Max output Power (Brake) of MEM</td>
<td>4100</td>
</tr>
<tr>
<td>PhMemCon</td>
<td>Output Power (Brake) of MEM in maximum CONT.</td>
<td>2100</td>
</tr>
<tr>
<td>TcoldMem</td>
<td>Min. Temperature (COLD) in armature winding</td>
<td>30</td>
</tr>
<tr>
<td>TCoolWat</td>
<td>Inlet Temperature of COOLing water MEM</td>
<td>296</td>
</tr>
<tr>
<td>ThotMem</td>
<td>Maximum Temperature (HOT) in armature winding</td>
<td>403</td>
</tr>
<tr>
<td>Uc</td>
<td>Terminal (U) voltage of commutator</td>
<td>13.85</td>
</tr>
<tr>
<td>UmaxMem</td>
<td>Max. [expected voltage] (U0) at terminals</td>
<td>785</td>
</tr>
<tr>
<td>WcdMem</td>
<td>Ratio between Width Cooler and Diameter Motor</td>
<td>0.80</td>
</tr>
<tr>
<td>Wvague</td>
<td>Width of VAGUE space</td>
<td>0.05</td>
</tr>
<tr>
<td>W</td>
<td>MCoolM</td>
<td>Ratio between gross Width MEM and net Width</td>
</tr>
<tr>
<td>XcentriM</td>
<td>Ratio between X centroid and Length of MEM</td>
<td>0.4</td>
</tr>
<tr>
<td>ZaMem</td>
<td>Number (Z) of MEM Armatures</td>
<td>2</td>
</tr>
<tr>
<td>ZfounD</td>
<td>Ratio Z-centroid Foundation and Diameter motor</td>
<td>0.3</td>
</tr>
<tr>
<td>Z Serie</td>
<td>Number (Z) of SERIE windings one armature</td>
<td>2</td>
</tr>
<tr>
<td>ZShunt</td>
<td>Number (Z) of SHUNT windings one armature</td>
<td>86</td>
</tr>
<tr>
<td>ainclShf</td>
<td>(α) angle of INCLination Shafing</td>
<td>1</td>
</tr>
<tr>
<td>TimeCon</td>
<td>Time warm up from COLD to HOT in CONT.</td>
<td>100</td>
</tr>
</tbody>
</table>
Note that the space sizing model can only predict the required space for box-shaped objects. The Main Electric Motor is not box-shaped as shown in figure 6.1. To overcome this limitation a minimum required contour is defined which takes into account the tilt angle of the shafting, see parameter: angle of INCLination Shafting.

An important technological constant for the Main Electric Motor designer is the maximum armature current density. A normal value for the current density of an air cooled electric motor is about 500 [A/cm²]. Figure 8.2 shows the variation of this parameter for a motor with different number of armatures. Current density can increase when new technology becomes available, such as directly water cooled windings. An increase of the current density decreases the diameter of the motor. However, when the diameter of the motor becomes to small to fit the number of pole pairs, the motor is designed with one pole pair less. Decreasing the number of poles increases the length of the motor. The figure shows that the effect of decreasing number of poles is significant. As a result, the highest armature current density will not always result into the smallest Main Electric Room.

![Graph showing the effect of armature current density and number of armatures on the length of the Main Electric Room](image-url)
8.1.3 Define and size inboard concept

Available space in the inboard concept is created by defining cells within cylindrical compartments. Figure 8.3 shows the inboard layout of spaces of the 3000 [t] submerged displacement submarine. The broken lines represent the equivalent spaces (for conical sections and spherical bulkheads), which are used to calculate the available and occupied area and volume in a cell.

![Figure 8.3 Existing concept and equivalent spaces](image)

All cell properties are sized during the definition of the cell, excluding the cells in a compartment which length is defined "soft". Within the space layout of the submarine, the main electric room, diesel generator room and battery room are defined as 'soft' compartments, as models are available for sizing the properties of the objects allocated to these compartments. After allocating objects to the cells, a part of the space becomes occupied: the length of the main electric room and diesel generator room appeared to be determined by the length requirements of the (relatively large) objects and the length of the battery room by the area requirements. Table 8.3 shows the growth of compartment length due to allocation of objects.

Before the first object is allocated to the MEM-room, the real length is already 6.89 [m] as the compartment has at the aft side a torispherical bulkhead and a conical section with 12.5 degrees conus angle. Note that only for the type one objects inboard shaft (1MTrans) and main electric motor (MEM) the available, occupied and free length is calculated. Before the allocation of the MEM, 2.79 [m] space length is available and 4.10 [m] is unavailable (due to width and height requirements in the conical section). Within the available length, 0.51 [m] is occupied by the shaft and as
a result only 2.28 [m] is free for the MEM. The MEM requires 3.81 [m] space length thus the length of the space must increase by 1.53 [m] to enable allocation of the MEM. The results also show that the shaft length is sufficiently long, as more than 0.5 m is occupied (by the shafting) before the main electric motor can be allocated. The equivalent length (length of a cylinder with same internal volume and diameter as compartment) is always smaller than the real length, indicating that the MEM-room size is not determined by area and/or volume requirements of any object.

Table 8.3  
<table>
<thead>
<tr>
<th>Designer ID</th>
<th>INBOARD BOAT CONCEPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>13-11-1997</td>
</tr>
<tr>
<td>Time</td>
<td>10:22:46</td>
</tr>
<tr>
<td>Space</td>
<td>Cell</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell number</td>
<td>9</td>
</tr>
<tr>
<td>Cell name</td>
<td>MEM-room</td>
</tr>
<tr>
<td>Short name</td>
<td>NE</td>
</tr>
<tr>
<td>Max. Gross Height</td>
<td>5.20 [m]</td>
</tr>
<tr>
<td>FrameHeight of Deck</td>
<td>0.000 [m]</td>
</tr>
<tr>
<td>Decktype</td>
<td>Does not exist</td>
</tr>
</tbody>
</table>

--- CELL RESULTS ---

BEFORE allocating of object | AFTER

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Num.</td>
<td>name</td>
<td>Length</td>
<td>Length</td>
<td>Length</td>
<td>Length</td>
<td>Length</td>
<td>Length</td>
</tr>
<tr>
<td>[m]</td>
<td>[m]</td>
<td>[m]</td>
<td>[m]</td>
<td>[m]</td>
<td>[m]</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>4221</td>
<td>Plane</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.89</td>
<td>0.03</td>
</tr>
<tr>
<td>2211</td>
<td>IMTrans</td>
<td>6.89</td>
<td>0.00</td>
<td>0.00</td>
<td>6.89</td>
<td>0.76</td>
<td>(steering actuators)</td>
</tr>
<tr>
<td>211</td>
<td>MEM</td>
<td>2.79</td>
<td>4.10</td>
<td>0.51</td>
<td>2.28</td>
<td>8.42</td>
<td>3.15</td>
</tr>
<tr>
<td>2123</td>
<td>MEMaux</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>8.62</td>
<td>3.15</td>
<td>(choppers)</td>
</tr>
<tr>
<td>TOTAL CELL</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>62</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After allocation of all inboard objects, space efficiencies are calculated. Table 8.4 shows typical net inboard space efficiencies for a 3000 [ton] submerged displacement submarine. The results can not be compared to (unknown) space efficiency values of the boat in reality. However the trend of these values along the different spaces seems realistic.

Table 8.4  Examples space efficiencies

<table>
<thead>
<tr>
<th>Space</th>
<th>Type compartment</th>
<th>Real length</th>
<th>Eq. net area</th>
<th>Eq. net volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine room with large equipment</td>
<td>soft</td>
<td>100</td>
<td>60 ±5</td>
<td>40 ±5</td>
</tr>
<tr>
<td>Engine room with small equipment</td>
<td>hard</td>
<td>-</td>
<td>50 ±20</td>
<td>25 ±10</td>
</tr>
<tr>
<td>Battery room, excl. side tanks</td>
<td>soft</td>
<td>-</td>
<td>75</td>
<td>80</td>
</tr>
<tr>
<td>Tank in lower part of conus</td>
<td>hard</td>
<td>-</td>
<td>-</td>
<td>70 ±10</td>
</tr>
<tr>
<td>Tank in lower part of cylinder</td>
<td>hard</td>
<td>-</td>
<td>-</td>
<td>100</td>
</tr>
</tbody>
</table>
The space efficiency of engine rooms to which relative large objects are allocated is slightly higher than the efficiencies of engine rooms to which relative small objects are allocated. Within the general arrangement drawing this difference is also observed as small objects require relatively more area and volume for service compared to the large objects. Batteries, which do not require any space for service between the objects, have a high area and volume efficiency which is only limited to the maximum available space due to its height requirement. Tanks allocated to a cell can achieve an extremely high volume efficiency. Difference between space efficiencies of tanks in conical pressure hull sections and cylindrical sections is caused by the equivalent compartment space approach. The space in a conical section which belongs in reality to the middle part of the compartment is shifted to the lower and upper parts of the equivalent compartment. As a consequence, the available space in a lower part of a conus is larger than in reality, which causes a lower volume efficiency. This limitation can be overcome by calculating the equivalent space for each cell instead of for each compartment.

8.1.4 Define and size the primary and inboard secondary structure

The maximum available space for primary and secondary structures is defined during the inboard concept definition, as the maximum allowable frame height. The frame height of the inboard primary and secondary structure is defined by the designer. This height must be chosen as accurately as possible because it determines the maximum available net inboard space in the boat to which all type 1 and 2 objects must be allocated. In this case the inboard frame height of the primary structure was chosen to be less than 300 [mm]. The height of the outboard frames is less strict, therefore the maximum value of these frames is set to 400 [mm]. The inboard frame height of the secondary structure is defined per deck. By using an equivalent structural thickness for each type of deck structure (fixed: 10 [mm], flexible mounted: 20 [mm], imaginary (gratings): 5 [mm]) the structural mass of the decks is calculated.

A non-linear optimisation algorithm is applied to determine the dimensions of the primary structure with the lowest production cost and which fulfills the strength constraints caused by the buckling phenomena and the maximum available frame height. Especially the overall buckling is sensitive to out-of-circularity of the cylindrical structure. Several methods for calculating the out-of-circularity are applied, see table 8.5. Figure 8.4 shows the effect of the different methods on the relation between the diving depth and the mass of the primary structure for a given safety factor.

Table 8.5 Out-of-circularity calculation methods

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>Out-Of-Circularity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 % of radius compartment [BS5500 design-code]</td>
<td></td>
</tr>
<tr>
<td>dependent on number of circumferential buckling waves [Faulkner, 1991]</td>
<td></td>
</tr>
<tr>
<td>dependent on number of welded plates in circumferential directions (4) and the circumferential buckling waves [Kaminski, 1996]</td>
<td></td>
</tr>
</tbody>
</table>
Figure 8.4  Relation between primary structure mass and diving depth for a given safety

From figure 8.4 is clear that the BS5500 design code predicts a more conservative value for the dimensions of the primary structure than the models of Faulkner or Kaminski which include the effect of number of circumferential buckling waves. Due to the discrete plate thickness, the mass of the pressure hull does not show a smooth figure when the diving depth increases.

When the structural dimensions of the primary structure of the 3000 [ton] submerged displacement submarine are applied, then it appeared that each compartment had a different safety factor. The safety factors are approximately 1 to 3 % higher for interframe buckling than required and 4 to 15% higher for overall buckling. These differences can partly be explained by the difference in geometry of pressure hull, as some conical sections contain two different cone angles in reality while the model contains only one. Another more important explanation is that the dimensions of the structure of the reference submarine have not been optimised for both interframe and overall collapse simultaneously and for each compartment separately. For example, for practical reasons only one or two different frame distances are usually applied along the pressure hull length. Note that the ratio between the dimensions of the structure usually varies along the pressure hull, however in the model these dimensions are chosen similar for all compartments.

The differences between the safety factors are not included in the optimisation process. Consequently, after optimisation the mass of the primary structure of the 3000 [ton] submerged displacement submarine has become lighter with a value between 0 and 13% of the original mass. 0%, when applying the BS5500 design code and 13% when applying the method of Faulkner.

8.1.5 Define and size outboard objects
Characteristic for outboard objects is the volume of displacement. Any object located outside the primary structure displaces an amount of seawater and must be able to resist seawater pressure at maximum diving depth. Therefore, most outboard objects are seawater and/or fuel tanks. Although these tanks are located outside the pressure hull.
no special structure is required for resisting seawater pressure. The pressure in these types of tanks are maintained equal to the seawater pressure, as these tanks have one or more openings to the surrounding seawater.

### 8.1.6 Define and size outboard concept

Definition of the outboard concept starts with the definition of the outer hull shape parameter values, such as tail angle, or prismatic coefficient of run or entrance section. If these values are unknown, then initially outer hull shape parameters of an existing submarine can be calculated.

From the longitudinal cross section of this submarine are measured: length of run, middle and entrance sections, the maximum radius and one (critical) point at the run and one at the entrance contour. Instead of values for the (critical) point at the run section, it is also possible to measure the tail angle.

Using these initial values for the shape parameters an outer hull is sized along the primary structure with a defined minimum distance between the outer and the pressure hull. Length of the run, middle and entrance sections are sized such that the outer hull obtains the defined shape parameters and at each cross section is the distance between primary and the outer hull structure larger than its defined minimum. The sized outer hull is shown to the designer for acceptance. Figure 8.5 shows the outer hull. If not acceptable, the designer can change one or more of the hull parameters.

![Figure 8.5 Outer hull](image)

After sizing the outer hull, added hulls and appendages are defined, sized and outboard objects are allocated to them. Table 8.6 shows typical outboard space efficiencies for a 3000 [ton] submerged displacement submarine.

<table>
<thead>
<tr>
<th>Space</th>
<th>Volume Eff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tanks in outer hull fore ship</td>
<td>80</td>
</tr>
<tr>
<td>Tanks in outer hull aft ship</td>
<td>100</td>
</tr>
<tr>
<td>Added hull</td>
<td>not yet</td>
</tr>
<tr>
<td>Appendages rudders/hydroplanes</td>
<td>5</td>
</tr>
<tr>
<td>Appendage sail</td>
<td>not yet</td>
</tr>
</tbody>
</table>

(At present) only tanks are allocated to the outer hull. The space efficiency of the aft outer hull is extremely high as it contains only tanks and almost no equipment.

135
The space efficiency of the appendages is low, as apart from the rudder stock, they are nearly completely free flooded. The space efficiencies of the added hull and sail cannot be calculated as almost no objects are (at present) allocated to them.

8.1.7 Define and size secondary outboard structure
The outboard secondary structure is sized using the structural area of the outer-, added hull and appendages. By using an equivalent structural thickness for each type of outboard structure, mass and volume of displacement are calculated. Table 8.7 shows the structural area, mass and resulting equivalent structural thickness for each outboard structure of the 3000 [ton] submerged displacement submarine.

<table>
<thead>
<tr>
<th>Table 8.7 Equivalent thickness of outboard structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural area according to model [m²]</td>
</tr>
<tr>
<td>Outer hull</td>
</tr>
<tr>
<td>Added hull</td>
</tr>
<tr>
<td>Appendages</td>
</tr>
</tbody>
</table>

The mass of the outer hull is in reality larger as the added hull is not present along the total length of the pressure hull. The mass of the added hull is for the same reason in reality smaller. Extending the model with a more accurate description of the length of the added hull can improve the accuracy of the prediction of the properties of the outboard secondary structure.

8.1.8 Determination of propulsion performance
The propulsion performance depends on the propulsion power - speed relation of the submarine. In most submarine design studies [Burcher, 1994][Jackson, 1992], the propulsion power requirement follows the ideal ‘Cube law’ since the Admiralty constant is assumed to be constant. However at lower speeds the propulsion power follows a curve steeper than the ideal curve, resulting in a higher brake power. Figure 8.6 shows the predicted propulsion power - speed relation and the ratio between the predicted power and the power which follows the ‘Cube law’. The ratio shows that the ‘Cube law’ is not valid at low speeds. At high speeds the ratio becomes almost one, as the submerged submarine does not generate or encounter waves. The figure also shows the effect of the added resistance due to the sail; a major propulsion power reduction is possible when the sail can be removed from the boat due to the non-penetrating mast developments.

The propulsion thrust is chosen to be delivered by a propeller. The open water characteristics of this propeller are determined from the Wageningen B-series [Oosterveld, 1975]. For a given number of blades and blade area ratio, the most efficient propeller is selected by the tool, which delivers the available power at the rotation rate in burst condition.
Figure 8.6  Propulsion power - speed and ideal cube law curve

As the propulsion power - speed relation does not follow the ‘cube law’ curve, the non-dimensional speed of advance (J) is not constant and thus also the open water efficiency is not constant. At low speeds the efficiency of the selected propeller is more than 9% less than the efficiency at burst speed.

The robustness of the propulsion power estimation model is checked by comparing the SUBCEM results to the results from a benchmark test [Prins, 1998]. The benchmark test includes the propulsion prediction of a 1800 [ton] submerged displacement submarine having a cylindrical midship length of approx. 60% of the overall length. The propulsion power calculations include calculations based on data from submarines with a relative short cylindrical midship section (less than 20% of overall length) and relative long cylindrical midship sections (more than 60% of overall length). The benchmark test also includes the results of a model basin test. Table 8.8 shows the results, and it is clear that the results of the delivered power prediction methods are different. The major differences in the calculations are found in the calculation of the propulsion thruster efficiency, which includes the hull efficiency, open water efficiency and relative rotative efficiency. The delivered power in snorking condition is, for all methods, higher than the value predicted by the model test. The scale effects in the model test results seem to become especially important when wave resistance of the snorking submarine must be taken into account.

Table 8.8  Comparison of delivered power prediction of a 1800 [ton] displ. submarine

<table>
<thead>
<tr>
<th>speed [kn]</th>
<th>Ratio betw. delivered power by calculation and by model test [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>based on data from boats with a small parallel midship</td>
</tr>
<tr>
<td>10. submerged</td>
<td>117</td>
</tr>
<tr>
<td>20. submerged</td>
<td>113</td>
</tr>
<tr>
<td>10. snorking</td>
<td>193</td>
</tr>
</tbody>
</table>

Note: no masts raised during snorking
The propeller is driven via a shaft by a main electric motor (MEM). This motor converts direct current power into torque at a rotation rate. Depending on the rotation rate of the motor, MEM armatures and batteries must be switched in different combinations of parallel and in series. These configurations depend on the maximum current through the armature and the maximum voltage at the terminals of the armature. Exceeding the maximum current or maximum voltage requires another configuration: for low speeds the batteries are configured in parallel and the armatures in series while for high speeds the batteries are configured in series and the armatures in parallel. The different configurations effect the efficiency of the main electric motor. Figure 8.7 shows the efficiency of the designed motor at different rotation rates and different voltages at the terminals of the motor.

![Efficiency Curve]

Figure 8.7  efficiency of a designed motor, for different rotation rates and voltages at the terminals of the motor

The broken line in figure 8.7 represents the limit where the current through the armature becomes larger than the maximum continuous current, the main electric motor is in the burst mode. Typical for burst mode is the overheating of the armature windings which can only be maintained for a limited time.

8.1.9 Define and size supplementary objects
Supplementary objects are 'correctors' on mass, volume of displacement and their centroids. The objects are initially allocated to spaces. After sizing the inboard and outboard concept and calculating the performance of the boat, the mass properties of the supplementary objects are determined. Typical examples of these objects are: the propulsor (whose size depends on the propulsion performance), the margin ballast (whose size depends on the mass of the boat as whole) and the outboard mechanical transmission (whose size depends on the relative location of the pressure and the outer hull).

8.1.10 Determine weight balance
The boat must be balanced, for energy, space and weight. As energy and space are balanced during the sizing process of the objects and the sizing process of the in- and outboard concept, only the weight balance remains to be achieved using fixed and/or
variable ballast. The centroid of this ballast is determined by centroids of gravity and buoyancy of the boat without ballast. Table 8.9 shows the weight of the boat excluding the sized and variable ballast.

### Table 8.9  Weight of the boat

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PH objects</td>
<td>43.61%</td>
<td>36.80 m</td>
<td>3.53 m</td>
<td>70.68 m</td>
<td>37.72 m</td>
</tr>
<tr>
<td>OH objects</td>
<td>24.18%</td>
<td>36.65 m</td>
<td>3.48 m</td>
<td>24.97 m</td>
<td>35.26 m</td>
</tr>
<tr>
<td>AddH objects</td>
<td>1.53%</td>
<td>36.64 m</td>
<td>7.29 m</td>
<td>1.09 m</td>
<td>12.70 m</td>
</tr>
<tr>
<td>App objects</td>
<td>1.56%</td>
<td>37.61 m</td>
<td>10.74 m</td>
<td>0.27 m</td>
<td>35.71 m</td>
</tr>
<tr>
<td>Sec struct Inb</td>
<td>2.62%</td>
<td>35.36 m</td>
<td>3.61 m</td>
<td>0.00 m</td>
<td>0.00 m</td>
</tr>
<tr>
<td>Prim struct</td>
<td>17.94%</td>
<td>37.84 m</td>
<td>4.20 m</td>
<td>1.96 m</td>
<td>38.62 m</td>
</tr>
<tr>
<td>Sec struct OH</td>
<td>4.93%</td>
<td>35.15 m</td>
<td>3.28 m</td>
<td>0.59 m</td>
<td>35.15 m</td>
</tr>
<tr>
<td>Sec struct AddH</td>
<td>2.34%</td>
<td>37.24 m</td>
<td>7.33 m</td>
<td>0.28 m</td>
<td>37.24 m</td>
</tr>
<tr>
<td>Sec struct App</td>
<td>1.29%</td>
<td>31.93 m</td>
<td>9.11 m</td>
<td>0.16 m</td>
<td>31.93 m</td>
</tr>
<tr>
<td>TOTAL boat</td>
<td>100.00%</td>
<td>36.59 m</td>
<td>3.96 m</td>
<td>100.00 m</td>
<td>36.83 m</td>
</tr>
</tbody>
</table>

By shifting the centroid of the ballast, the centre of gravity (including the ballast) and of buoyancy of the boat are located at the same longitudinal position. For the 3000 [ton] submerged displacement submarine the amount of fixed and variable ballast is about 8% of its displacement at 58% of the overall length (from aft) and at 45% of the overall diameter (from keel). From these values it is concluded that the design is feasible as the amount of ballast has a positive value and/or the centroid of the ballast is located inside the outer hull contour.

#### 8.1.11  Determine hydrostatic performance

The hydrostatic performance shows the (neutral) trim and buoyancy capacity during submerged condition. Some objects can vary during the mission. These objects are identified by the attribute ‘variable weight’ and can be allocated to the trim/weight-compensation system, main ballast system or consumables. Typical for the trim/weight-compensation objects is that they only have volume when allocated to a space and do not contain any mass. The amount of seawater filled in this volume determines the mass of these objects and accordingly the size of the trim polygon. For each consumable the percentage of consumption is defined for three different loading conditions. Using these defined percentages, the amount of trim/compensation mass and longitudinal moment relative to the centre of buoyancy of the boat are calculated. The combination of mass and moment is plotted in the trim polygon for the two defined...
conditions with the boat displacing heavy, average and light sea water. Figure 8.8 shows the trim polygon for a 3000 [ton] submerged displacement submarine. Initially the loading conditions were located outside the polygon. These different combinations could be located within the polygon by adding a fixed ballast mass of approximately 6% of the submerged displacement at 10% of length of the boat forward of the centre of buoyancy. The reference submarine has a fix ballast mass which is less than 1% of the submerged displacement lower and the longitudinal position is 2% less forward. Finally, all six combinations of mass and moment are located within the polygon, thus neutral trim and buoyancy can be achieved for these different conditions.

By locating this ballast at approximately 20% of the overall diameter above the keel, the boat fulfills the minimum righting moment capability, as the distance between the centre of gravity and metacentre is for both loading conditions in the range of 3 to 4% of the maximum pressure hull diameter. The reference submarine has its fixed ballast more than 10% of the overall diameter higher, however note that the centre of gravity of the predicted submerged displacement is only 0.3% higher than the reference submarine.

![Trim polygon diagram](image)

**Figure 8.8 Trim polygon**

Objects fulfilling the main ballast function determine the amount of reserve of buoyancy during surfaced condition. The reserve of buoyancy is independent from the loading conditions of the boat. Due to the defined double hull concept for the 3000 [ton] submerged displacement submarine large ballast tanks could be allocated to the forward and aft part of the outer hull. Emptying these ballast tanks generates a 14% reserve of buoyancy or 12% reserve of weight. Be aware that the blowable mass of the main ballast tanks is stated in reserve of buoyancy as a percentage of the surfaced displacement and in reserve of weight as percentage of submerged displacement.
8.1.12 **Determine energy-autonomy**

The energy-autonomy performance shows the time a certain amount of energy can be supplied during a part of a mission or during the total mission. Energy consumers are divided into consumers required for propulsion and for other functions. The amount of energy required for propulsion is dependent on the speed of the boat during submerged or surfaced condition.

Figure 8.9 shows a typical example of the submerged endurance as a function of the submerged speed for a fixed discharge range of the batteries. The presented (assumed) function of the **Hoteload** gives the power demand by all functions except the propulsion function. The endurance shows discontinuities, which are caused by different battery and main electric motor armature configurations. The endurance at high speeds is limited by the maximum allowable current. This maximum allowable current depends on the type of switches applied in the direct current distribution system. Modern switches, used in submarine systems, can switch currents with a maximum value of about 3200 Amperes. During discharge the voltage of the battery cells drops and thus for a required amount of propulsion power the current through the cells increases. The voltage of lead acid batteries drops not only due to current through the cells but also due to increasing discharge state. As a result, the current through the main electric armatures exceeds the maximum allowable value during burst speed long before the cells are fully discharged. For the burst speed of the 3000 [ton] submerged displacement submarine the discharge rate cannot be achieved below 55% of the discharge state which can be achieved at low speed. When starting from 0% discharge state (fully loaded cells) this discharge state is reached after approx. 1.5% of the endurance at 2 [kn] submerged speed. However this discharge state can not be achieved as the burst condition can only be maintained during approx. ½ this time until the armature windings become overheated.

![Endurance vs Submerged Speed](image)

**Figure 8.9** Typical deep discharge time for different speeds

Note: battery discharge range 0-80% discharged capacity.

Figure 8.10 shows a typical example of the indiscretion ratio and total range of the boat as a function of the speed of advance and snorting speed. A fixed delay in time is taken into account for the period the snorkel top is above the water and the charging process starts. This time delay is not part of the charge time however it is part of the snorting
period as calculated in the indiscretion ratio. The indiscretion ratio is therefore also called 'noise indiscretion ratio' [Heggstad, 1984].

![Graph showing IR rel. to IR at 2 kn Submerged speed [%] vs Speed of advance [kn]](image)

![Graph showing Range [%] of maximum vs Speed of advance [kn]](image)

Figure 8.10 Typical figure for presenting (noise-)indiscretion ratio and total range
Note: battery (dis-)charge cycle range 20-30% discharged capacity.

### 8.2 Concept variation cases

To illustrate the applicability of the tool for re-design a limited parametric survey is performed around the baseline concept described in the previous sub-paragraph. Re-design implies (some) similarity between a new design problem and a past problem, and assumes that the past solution can be re-used. Re-design is predominantly a form of routine design, however the modifications to the solution process require exploratory or even creative design tasks. This type of design is widely applied in industry, as extending or modifying designs limits the search space for a solution and thus saves development time.

The re-design of the submarine can be divided into re-design of objects and/or layouts. The re-design of objects contains parametric variations of object sizes and show their effect on the balance and performance of the boat. The re-design of layouts contains parametric variations of the size and layout of spaces and shows its effect on the balance and performance of the boat. Obviously, the range of parametric variations effect the users' confidence that the finally selected design is the best alternative.

These surveys not only show the kind of design problems which can be solved, but also emphasise a number of experiences reported while using the tool. These experiences
are evaluated in the next paragraph, to rate the efficiency of the tool. Below, a selection of variations is made, based on submarine design questions which have been reported in recent literature e.g. [Jackson, 1992]:

- Effect of low speed main electric motors on size and propulsion performance of the boat
- Effect of material properties of primary structure on diving depth performance
- Effect of battery types and/or air independent energy supply system on size and propulsion performance of the boat
- Effect of double-single hull choice on size, propulsion and hydrostatic performance of the boat
- Problem reversing: initially the propulsion system is sized and the propulsion performance is calculated, when reversing this problem the propulsion performance becomes input and the propulsion system is sized to achieve the required performance.

8.2.1 Propulsion object (main electric motor) variation
The development of new converter fed permanent field motors introduce the possibility of low speed high torque motors. This variation case examines the effects of the rotation rate of the direct current driven main electric motor on the overall propulsion performance and dimensions of the boat.

Variation study
The rotation rate of the main electric motor effects the size and performance of the motor itself but also the size and performance of the mechanical transmission and the propulsor. Decreasing the rotation rate causes two main effects: the propulsion efficiency of the propulsor becomes higher and the size of the main electric motor increases. The increasing diameter of the motor causes a more forward location of the motor in the aft conical section of the pressure hull, as the required height and width of the motor increase. This more forward location combined with the enlarged motor requires a longer aft compartment to enable the allocation of the motor to this space. A longer compartment effects the size and performance of the entire boat, such as increasing displacement and mass of the pressure hull and increasing resistance of the boat.

Assumptions
In the analysis the following assumptions and approximations are applied:
- The calculations have been carried out for submarines with the same outer hull shape. The shape parameter values describing the entrance and run sections do not change.

Results of variation study
Figure 8.11 shows the effect of altering the rotation rate on the deep discharge time for low speed. This figure clearly shows an optimum for the rotation rate. At rotation rates below the optimum, the effect of increasing boat size on the resistance is larger than
the effect on the propulsion efficiency, and at rotation rates above the optimum both effects invert. At very low rotation rates (below 130 [rpm]) the diameter of the armature enlarges such that an additional pole pair is applied. Extending the number of pole pairs increases the efficiency of the motor and decreases the length of the motor. This explains the discontinuity in the figure, represented by a dashed line. The shape of the optimum is not specific. This implies a greater tolerance to the selection of the rotation rate. Other size or performance parameters might therefore have a larger impact on the selected rotation rate. The figure also shows the effect of altering the rotation rate on the time period after which the motor becomes overheated in burst condition (burst time), amount of ballast in the boat, and the length of the pressure hull. Reducing the rotation rate increases the burst time significantly as the mass of the armature windings increases. The mass of the motor also gives the space to which the main electric motor is allocated a higher density than sea water, as the figures indicate that increasing the pressure hull length decreases the amount of required ballast in the boat. Discontinuities in the figures are caused by the number of pole pairs, as also observed in the deep discharge curve.

![Graphs showing relationship between rotation rate, endurance, and other parameters](image)

**Figure 8.11** Time discharge deep, burst time, mass and position fixed ballast and length pressure hull versus rotation rate in burst condition
Discussion
The variation of the rotation rate of the main electric motor has an impact on the size of the main electric motor, size of room in which the motor is located, weight of the motor and structure of the room, performance of the motor, shafting and propeller. During the traditional design process each impact is studied separately, often by separate departments in the design office (e.g. structural department, naval architectural department and the electrical department). Separation of a study between different departments can become time consuming and involves the risk for inconsistencies between the results. Within SUBCEM the rotation rate variation is done within one tool, in which the knowledge from the different departments is available. The impact of rotation rate is studied in a time efficient way and with a high consistency between the answers on the different aspects.

8.2.2 Primary structure variation
Typically a lot of design effort is put into the sizing process of the primary structure as for a 3000 [ton] submerged displacement submarine the sized primary structure generates about 16% of its mass and a significant part of the overall labour cost [Lambert, 1996]. A discussion regarding the application of high yield steel or a moderate strength commercial steel for the primary structure can be supported by the tool. Application of moderate strength steel can reduce the total man hours with more than 25% in comparison to high tensile steel which require a temperature controlled environment before it can be welded. However, the ability to dive to greater depths enables the submarine to exploit more ocean layers, which makes the submarine more difficult to detect and it also provides the ability to operate at higher speeds (at a certain depth). This variation case examines the effect of material properties on various deep diving depths of the boat.

Variation study
For a given inboard concept the material properties of the primary structure are varied. Materials properties can be found in literature for different materials. Table 8.10 shows properties of commonly applied materials for the primary structure. The effect of different types of materials on the mass of the primary structure is analysed for deep diving depths between 150 and 500 metres.

Table 8.10 Structural material properties [Mac Gregor,1990]

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield stress [MPa]</th>
<th>Compressive modulus [GPa]</th>
<th>Density [t/m³]</th>
<th>Poisson ratio [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe 355</td>
<td>355</td>
<td>206</td>
<td>0.041</td>
<td>7.86</td>
</tr>
<tr>
<td>HY 80 steel</td>
<td>550</td>
<td>207</td>
<td>0.052</td>
<td>7.86</td>
</tr>
<tr>
<td>HY 100 steel</td>
<td>650</td>
<td>206</td>
<td>0.056</td>
<td>7.86</td>
</tr>
<tr>
<td>Titanium 1M1 31B alloy</td>
<td>830</td>
<td>106</td>
<td>0.088</td>
<td>4.54</td>
</tr>
<tr>
<td>Aluminium H15 alloy</td>
<td>445</td>
<td>72</td>
<td>0.079</td>
<td>2.80</td>
</tr>
</tbody>
</table>

σ: Compressive yield stress
E: Young’s modulus
Assumptions
In the analysis the following assumptions and approximations are applied:
- The calculations have been carried out for primary structure with constant ratios between the different dimensions of the T-frame.
- The effect of seawater pressure on the inboard equipment exposed to this pressure is not taken into account.

Results of variation study
Figure 8.12 shows the ratio between mass primary structure and displacement for different deep diving depths. Structures made of aluminium or titanium show the smallest primary mass for the given inboard concept. This effect becomes even larger when the deep diving depth of the boat increases. However due to technical (e.g. weldability, homogeneity, fatigue and creep) and cost reasons steel structures are (currently) preferred.

The slope of the lines in the figure decreases when the square root of the ratio between the compressive strength and Young’s modulus increases. Especially for materials with smaller yield stress the overall collapse due to reaching yield in a frame becomes the dominant failure mode. To avoid overall collapse both shell thickness and frame dimensions have to increase causing a significant increase of the primary structure mass.

![Graph showing DDD versus ratio between mass primary structure and submerged displacement]

Figure 8.12  DDD versus ratio between mass primary structure and displacement

Discussion
The question which material should be applied for submarines is raised many times in literature [Heggstad, 1982][Gorman, 1991][Morandi, 1994][Lambert, 1996]. Within these studies only a limited number of alternative compartments lengths and diameters are examined. Also, these studies usually do not consider the limitation of the frame height due to internal layout. Within SUBCEM the structure of each compartment is sized using an optimisation procedure which takes the maximum available in- or outboard space for frames into account. Using this procedure an accurate budget for the mass of the total
pressure hull is achieved. The calculation is integrated in the design tool, making the calculation of the impact of a change in the internal layout on the mass of the primary structure possible. For example, when the boat becomes weight critical it is possible to examine the effect of an alternative material.

8.2.3 Energy storage variation

Two important operational characteristics of a submarine determine its detectability during anti-submarine warfare: noise and its operational envelope.

An important source of noise emission are the running diesel generators during snorting operation. Despite the suppression of this noise by the use of flexible couplings and double-elastic mountings there remains a chance of detection at a relative great distance. The obvious counteraction is to make the snorting period as short as possible.

The operational envelope is the ocean space in which the submarine might be some time span after an initial detection. This envelope depends on the diving and the speed-endurance capability. The ability to dive to greater depths (see: primary structure variation) enables the submarine to exploit more ocean layers, making submarine detection more difficult. It also provides an ability to operate at higher speeds (at a certain depth) as the vertical plane of the safety envelope increases. The ability to sustain a higher speed for an elongated period enables the submarine to enlarge its operational envelope. This endurance depends on the available air independent power and energy.

The development of energy supply systems which reduces the exposure to detection during snorting and expands the submerged endurance has been in two directions. First, the development of new battery types and second, the development of energy conversion systems which transform chemical energy into electrical energy independent from ambient air. Both developments are investigated to show the effect on the propulsion performance of the boat both at low and at high speeds.

New battery types

Typical objectives for batteries, which support short charging periods and extended discharge periods are: low internal resistance, high open cell voltage which does not drop during discharge, no voltage increment between discharging and charging, high maximum voltage before overcharging or gassing occurs and high energy content per unit mass and per unit volume. Table 8.11 shows the practical characteristics of two modern batteries. ‘Practical’ means that the characteristics are based on a total battery system, including seatings, thermal insulation and electrical connections.

The Zebra cell has improved performance compared to a modern lead acid cell for almost all characteristics [Dustmann, 1992]. Two characteristics are not (yet) improved: internal resistance and the capacity per unit volume. Recent developments have decreased the internal resistance by more than 50% since these figures were presented in 1992 [Sahm, 1994].
Table 8.11  Battery properties

<table>
<thead>
<tr>
<th>Important battery characteristics</th>
<th>Double Decker Pb/PbO$_2$ Lead Acid $^{1)}$</th>
<th>High temp. Na/NiCl$_2$ Zebra $^{2)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature (°C)</td>
<td>Room Temp.</td>
<td>325</td>
</tr>
<tr>
<td>Maximum height (m)</td>
<td>1.4</td>
<td>No. boxes times 0.315</td>
</tr>
<tr>
<td>Max. open cell voltage (V)</td>
<td>2.0 till 2.1</td>
<td>2.58</td>
</tr>
<tr>
<td>Open cell voltage decrease</td>
<td>see figure 8.13</td>
<td></td>
</tr>
<tr>
<td>Voltage increment between</td>
<td></td>
<td></td>
</tr>
<tr>
<td>discharging and charging (V)</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>Density (l/m$^2$)</td>
<td>3.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Specific capacity at 5 hours</td>
<td>19.7</td>
<td>33.2</td>
</tr>
<tr>
<td>discharge rate (Ah/kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific capacity at 100 hours</td>
<td>24.0</td>
<td>33.2</td>
</tr>
<tr>
<td>discharge rate (Ah/kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacity as function of actual</td>
<td>see figure 8.13</td>
<td></td>
</tr>
<tr>
<td>current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proven number of charge-</td>
<td>600</td>
<td>870</td>
</tr>
<tr>
<td>discharge cycles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal resistance</td>
<td>see figure 8.13</td>
<td></td>
</tr>
</tbody>
</table>

Notes 1. [Pel, 1995a]  
2. [AEG, 1995]

Figure 8.13  Battery cell characteristics

Much attention during the development of the new battery types is given to the increase of battery capacity per unit mass. In spite of the increase of capacity per unit mass for the Zebra battery relative to the lead acid battery (more than 68% at 5 hours discharge and 38% at 100 hours discharge) the new battery type has a lower battery capacity per unit volume [Varta, 1991] relative to the lead acid battery (more than 10% less capacity...
at 5 hours discharge and more than 26% less capacity at 100 hours discharge). As a consequence, replacing the lead acid batteries in a submarine by the Zebra battery requires more space in the battery compartment. In favour of the Zebra battery is the ability to make the cells into a stack, allowing different stack heights along the cross section. This increases the space efficiency in the battery space, see figure 8.14. As the Zebra battery does not require maintenance or repair during its operation, a minimum service space is required above the cells. When a cell fails during operation, it still remains conductive due to beta alumina which separates the negative from the positive electrode.

![Service and auxiliary equipment space](image)

**Figure 8.14** Cross section battery compartment, Lead acid and Zebra

**Variation study**

The effect of new battery types on the maximum endurance for different submerged speeds is examined by variation of the type and size of battery cells within the same battery compartment. The battery compartment can contain 2x 210 lead acid cells (2x 130 ton) containing 12400 Ah at 5 hours discharge. The same battery compartment can contain 2x 210 Zebra cells (2x 91 ton) containing 14500 Ah at 5 hours discharge (each cell consists of 5x 2900 Ah cells in parallel).

**Results of variation study**

Figure 8.15 shows the effect of type of battery cells on the maximum discharge time for different submerged speeds.

![Discharge time relative to max. endurance at DD battery](image)

**Figure 8.15** First part: maximum discharge time versus submerged speed
Figure 8.15 Second part: maximum discharge state versus submerged speed

Two major effects explain the difference between the discharge time at high speeds of the lead acid and the zebra cell: the current and the capacity. The first difference has an impact on the current through the main electric motor armatures. During discharge the battery cell voltage decreases, requiring a higher current for the same power. However, the maximum current through the main electric motor armatures is limited, thus the maximum discharge state is also limited, this is shown in figure 8.15. The second difference has a direct impact on the maximum discharge time as the discharge capacity decreases for the battery types differently at higher currents.

Discussion
Initially the models implemented in SUBCEM contained knowledge about the traditional lead acid batteries. New battery types are becoming available. As the tool is able to present the knowledge about batteries in a structured way to the user, knowledge about the new battery types could be added in a short time. Without re-writing the knowledge about the lead acid batteries, the knowledge about a new type of battery could be added. During the calculation of the discharge time at high speeds, new relations are selected which describe the behaviour of the zebra battery.

Air independent power supply
Different types of air independent power supply systems have been developed [Knaack, 1991]. As an example of such systems the closed-cycle diesel (CCD) is integrated into the boat described in the 'run through' case (see the previous paragraph). This system consumes oxygen during the conversion of chemical energy to electrical energy. The oxygen is stored cryogenically onboard (liquefied oxygen - LOX), as other means of storage require more volume and/or are less safe. The amount of oxygen and/or fuel limits the air independent endurance of the boat. Once the oxygen has been used, the boat becomes just a conventional diesel-electric submarine, until it can return to base for replenishment.

Variation study
The effect of a closed cycle diesel power supply on the maximum endurance and indiscretion ratio for different submerged speeds are examined in two ways; first by
replacing a battery and/or diesel engine(s) by a CCD system and second by adding a new compartment which includes the CCD system and/or the LOX tanks.

Results of variation study
One battery described in the ‘run through’ case can be replaced by LOX tankage containing 28 ton LOX. Maintaining the same number of battery cells, only half the battery capacity can be located. Within the diesel generator room two options are investigated: replacement of one 1MW diesel generator set by one 300 kW CCD system, and replacement of three 1MW diesel generator sets by three Open-Closed Cycle Diesel (OCCD) systems with a total output of 1200 kW in closed cycle and 1365 kW in open cycle mode. The maximum hotload is assumed to be 175 kW and at submerged speeds below 12 knots this load is assumed to decrease down to a minimum value of 122.5 kW at 5 knots. During recovery operation, the (O)CCD systems runs at maximum power output, the energy is supplied to the propulsion system, the hotload and the surplus is used to charge the batteries up to 20% of the discharge capacity at 100 hours discharge rate. During submerged operation the energy is supplied by the batteries by discharging them to 30% of the discharge capacity at 100 hours discharge rate.

Figure 8.16 shows the endurance and range as function of the speed of advance when the boat is alternating between the recovery and submerged operation. The OCCD option has much more air-independent power available, enabling a much shorter charging time compared to the CCD option. As a consequence, the OCCD option has a higher speed of advance resulting into a higher fuel consumption and thus decreases the endurance, but it also results into a higher optimum range compared to the CCD option.

![Endurance vs Speed of advance](image1.png)
![Range vs Speed of advance](image2.png)

Figure 8.16 Effect of (O)CCD on endurance, range and speed of advance
Reducing the battery capacity effects the high speed endurance of the boat (see also “New battery types” case). The battery compartment can contain 2x 210 6200 Ah lead acid cells, or 2x 210 7250 Ah Zebra cells (each cell consists of 5x 1450 Ah cells in parallel). Figure 8.17 shows the effect of the battery capacity reduction on the high speed performance. Increasing internal resistance reduces the discharge time. Burst speed becomes even impossible (due to a discharge current above 3200 A) when double decker lead acid cells are applied.

![Discharge time relative to run through case graph](image)

**Figure 8.17** Effect of battery capacity reduction on burst speed endurance

Although for a 300 kW CCD system and a 28 ton LOX tank, the boat can be submerged continuously during less than 6% of the mission time, the overall performance does not necessarily increase. Reducing the number of diesel generator sets from three to two increases the indiscrétion ratio during the non-air independent propulsion operation time. Figure 8.18 shows the impact of reducing the diesel generator power on the overall indiscrétion ratio relative to the ‘run through’ case. The overall indiscrétion ratio represents the ratio between the snorting time and the total submerged time.

![Overall Increase relative to run through case graph](image)

**Figure 8.18** Effect of replacing one battery and Diesel Generator Set(s) by an (O)CCD system
To improve the overall indiscretion ratio and maximum submerged endurance both the amount of air independent power supply and the amount of LOX and/or fuel must increase. Increasing these parameters can only be achieved by larger components, requiring more space within the boat. The space to accommodate these components can be found by adding a new compartment. The chosen location of the compartment is in front of the main electric motor room. Within this case, the available space above the tanks determines the amount of air independent power which can be installed.

Figure 8.19 shows the effect of LOX tankage size on the elongation of the compartment. Due to the service space (0.5 [m] at front and aft side of the tank) and the torispherical bulkheads of the tanks, the minimum tank length is 3.3 [m]. The insulation thickness is sized to allow a maximum oxygen boil-off rate of 0.5% per day. The figure shows a significant increase of the insulation thickness for smaller tank lengths.

Figure 8.19  Tank capacity versus tank length

The larger boat increases the resistance, resulting in a 2% to 5% lower burst speed when respectively a 25 ton to 75 ton LOX tankage is installed. The space above the tankage is used for a CCD system. Three tankage sizes are investigated: 28, 50 and 75 ton LOX. The space above the LOX tankage is suitable for respectively a 300 kW, 500 kW and 700 kW CCD system. Figure 8.20 shows the Recovery Ratio and Overall Indiscretion Ratio of the boat equipped with the CCD system. Note that the recovery speed at which the recovery ratio becomes 100% is called the speed at balanced condition. A recovery speed above the speed at balanced condition is impossible and the overall indiscretion ratio becomes equal to the indiscretion ratio of the boat. The boat with the larger CCD system has a higher indiscretion ratio as she has more resistance and thus requires more propulsion power for the same snorting speed.
Figure 8.20  Effect of CCD power and LOX tank size on the energy supply performance

For a totally submerged operation the optimum speed of advance depends on the installed CCD power. Figure 8.21 shows that for a recovery speed of 2 [kn] a larger CCD system allows a higher optimum speed of advance. The figure also shows that for low submerged speeds the total submerged endurance is mainly dependent on the installed LOX tank size.

Figure 8.21  Effect of CCD power and LOX tank size on the energy supply performance of the boat during totally submerged operation.
The CCD system is allocated to a compartment which is added to the concept. The bulkheads at both sides of the compartment are watertight to allow integration of the compartment without changing the structure of the existing compartments. The available space between the pressure hull and outer hull (outer hull space) is used for weight compensation tankage and additional fuel storage. Adding the CCD system effects the mass balance of the boat. Figure 8.22 shows the effect of LOX tank size (and CCD power) on the mass and centroid of gravity of the boat. The boat includes 80 [t] additional fuel in the outer hull space for the smallest CCD system and 165 [t] for the largest. To achieve a similar neutral buoyancy/trim capability and righting moment capability as the boat without CCD system, the location and amount of fixed ballast is changed according to figure 8.22.

![Graph showing mass balance](image)

**Figure 8.22** CCD system versus mass balance

**Discussion of the results**

Knowledge about CCD systems, such as the space/weight requirements and effect on energy supply performance, is added to SUBCEM without effecting the existing model of the 3000 ton submerged displacement boat. By removing equipment, installation of an air independent power supply system in the boat is possible. However the performance calculations show that the energy supply of the boat can only be improved during a limited part of the mission, while during the remaining part of the mission this performance decreases. Adding a compartment to the boat improves the overall energy supply performance. However this has a major impact on the boat's weight and space balance. While in a traditional design process each consequence is determined in a
separate calculation, the tool supports the calculation of these consequences in an integrated way: the size of the system, the length of the compartment, the size of the primary structure, the available space in the outer hull for tankage, the size of the trimpolygon etcetera. By integrating these calculations the effort to show the effect of alternative CCD system sizes on the performance of the boat is reduced considerably.

8.2.4 Double versus single hull

With more emphasis today being placed on shallow water operations, and the increased risk of mine or depth charge attack, it becomes worth to investigate the use of the double hull concept to improve survivability. However the question now arises which concept generates a smaller boat? Is it the single hull boat, as it has more flexibility in layout configuration [Prins, 1996], or is it the double hull boat, as this concept has the advantage of outboard (fossil fuel) tankage [Jackson, 1992]?

Variation study

This variation study examines the effect of re-designing a double hull to a single hull boat on the overall size of the submarine. Three different outer hull diameters are investigated, one equal to the maximum diameter of the double hull boat and the other two are less than this diameter. These diameters are chosen such that the overall length of the single hull boat is smaller, equal and larger than the length of the double hull boat.

Assumptions

- Layout and installed equipment of the variants must be as similar as possible, see figure 8.23. Thus the objects are allocated to similar spaces except from the outboard tankage in the double hull boat which becomes inboard tankage below the first deck from the base. Note that the space for fuel oil tankage is determined by the available inboard space.
- All variants must have the same free effective area for allocating all remaining equipment within the pressure hull. The effective area is considered to have a height of at least 1.4 [m]

![Figure 8.23 Double versus single hull space layout](image-url)
Results of variation study
Changing the layout of the boat from a double hull boat to a single hull boat results in a shorter boat when the maximum diameter of the single hull boat is equal to the maximum diameter of the double hull boat. When the maximum diameter of the single hull boat is reduced with 0.2 [m] the length becomes approximately equal to the length of the double hull boat. Further reduction of the maximum diameter of the single hull boat increases the length of the boat. Figure 8.24 shows the resulting overall length and the consequences for the mass of the boat (excl. ballast).

![Graph](image)

Figure 8.24  Effect of maximum outer hull diameter on the length and mass of the boat
Note: single hull boat is presented by closed markers and double hull by an open marker

The descending line for the mass of the boat is explained by two major effects: the changing mass of the fuel capacity and the mass of the primary and secondary structure. Both effects are shown in figure 8.25. The fuel capacity is significantly lower for the single hull boat. The capacity decreases when the hull diameter becomes smaller as the tanktop is defined lower in the boat to obtain sufficient deckheight for the equipment above the tankage. The figure also shows that the structural mass is significant higher for all single hull boats. The 8 [m] diameter boat has the lowest structural mass of the single hull boats. This is mainly caused by the primary mass of the largest compartment, which has a more favourable diameter and length for sizing a light weight structure than the other two boats.

![Graph](image)

Figure 8.25  Effect of maximum outer hull diameter on fuel and structural mass of the boat
The changing layout has a major effect on the centre of gravity of the boat. To achieve a similar neutral buoyancy/trim capability and righting moment capability as the double hull boat, the location and amount of fixed ballast is changed according to figure 8.26. Single hull boats with a large maximum diameter have a lower centre of gravity than the double hull boat. However when the diameter of the single hull boat becomes smaller, space requirements drive the components to a higher position in the boat, resulting in a higher centre of gravity thus decreasing the location of the fixed ballast. The single hull boats have their fixed ballast more aftward. However, for longer single hull boats the heavy machinery in the engine rooms drives the longitudinal centre of gravity more aftward requiring a more forward location of the fixed ballast.

![Graph showing effect of maximum outer hull diameter on the location and amount of fixed ballast](image)

Figure 8.26 Effect of maximum outer hull diameter on location and amount of fixed ballast

The changing layout also affects the fineness ratio (length to diameter ratio) and prismatic coefficient. Both geometrical parameters effect the propulsion performance of the boat, see figure 8.27. As explained in chapter six the minimum total drag is found at a fineness ratio 6-7 and a prismatic coefficient of 0.60-0.62. The burst speed calculations show both effects, as the speed reduces when the fineness ratio and prismatic coefficient move away from their optimum values.

![Graph showing effect of maximum outer hull diameter on fineness ratio, prismatic coefficient and burst speed of the boat](image)

Figure 8.27 Effect of maximum outer hull diameter on fineness ratio, prismatic coefficient and burst speed of the boat
Discussion of the results
This case shows the ability of the tool to change the lay-out of the boat from a double hull concept to several single hull concepts. In the traditional design process this change would require a complete re-design of the boat. Using SUBCEM the effect of this kind of changes on the space utilization, displacement, stability, structural dimensions and propulsion performance can be shown. Although the selection of double or single hull concept depends on many factors, the above presented results gives a number of quantitative considerations which can be used to support the choice for either a single or a double hull boat.

8.2.5 Problem reversing
The purpose of this case is to illustrate the ability of SUBCEM to reverse answer to question. Within the ‘run through’ case (as described in the previous paragraph) the propulsion system is sized and the propulsion performance is calculated. In this case the problem is reversed: the propulsion performance becomes input and the propulsion system is sized to achieve the required performance.

Variation study
The brake power and size of the main electric motor, including the effect on the size of the overall boat, is examined for a requested submerged speed of 19, 22 and 25 [kn]. To show that the results are the same for the opposite way of calculation, also the submerged speed is calculated for brake powers between 3500 and 9000 kW.

Results of problem reversing study
Starting from the ‘run through’ case, the effect of increasing burst speed on the required brake power is shown in Figure 8.28. The three markers are calculated by the reversed problem. The line is calculated by a straight forward parameter variation. Both calculations give the same results. Within the calculation is included the effect of a larger MEM on the size of the boat. Figure 8.28 also shows the growth of the main electric motor and the length of the boat. The length growth of the boat is larger as the motor not only increases in length but also in height and width, causing a relative more forward location of the motor in the main electric motor space. The effect of the larger boat on the required propulsion power is taken into account, which increases the required power 1 to 3% (for 25 to 22 knots).

Figure 8.28 Required brake power and length growth of boat (due to MEM) versus burst speed
Discussion of the results
The answer of a reversed problem can only be achieved when a correct template is built. As for (most of) the relations the dependency directions of the mathematical relationships are fixed in order to avoid too much entropy between the parameters in the knowledge base for solving foreseen questions. Problem reversing has not been a foreseen question, thus the entropy between the parameters must increase before the problem can be solved. In this case, at least the following relation must be able to calculate the parameters in two directions:

\[ v = \frac{P_d \eta_d}{T} \]

In which:

- \( v \) Submerged speed [m/s]
- \( P_d \) Power delivered to propulsor [kW]
- \( T \) Thrust delivered by propulsor [kN]
- \( \eta_d \) Propulsion efficiency [-]

Reversing the problem still requires a strategy for solving the problem stepwise. Just asking for the brake power of the MEM in burst condition causes a jumping to conclusions: the reasoner selects the wrong relations and cannot find the correct path. The reversed problem is solved by the following sequence of design tasks. First the in-and outboard concept (DefOutConc) is determined using a given value for the brake power of the MEM in burst condition (PbMemBurst). Separately the power at shaft (PsBurst) is determined for a given burst speed, using the relation between the Resistance and speed. Of course the given value for the brake power is not correctly chosen to deliver the required power to the shaft. Thus, the brake power is made unknown and the relation between the power at the shaft and the brake power of the MEM is accepted in the template. A non-linear set of 150 equations with 16 degrees of freedom has been built and must be solved simultaneously. Observed in the case is that problem reversing is not always numerically possible. When using Newton-Raphson's method the solver might try to find a solution in the wrong direction as the Jacobian based on a particular set of starting values initially does not produce the correct values. When correct starting values are applied, the Newton-Raphson method is able to find the solution of the reversed problem. Figure 8.29 shows the value of the brake power after each iteration step.

![Graph showing brake power MEM difference relative to final answer](image)

**Figure 8.29** After each iteration value of brake power MEM required for 19 [kn] burst speed
8.3 Usability of design tool

To evaluate the usability of a design tool subjective measures of effectiveness are used. The effectiveness measures the value of the tool to the personnel and organisation which uses it. The emphasis in this paragraph is on the opinion of the user(s) about the tool regarding its strengths and weaknesses for actually supporting him or her while performing a design task. In literature an approach is presented by Adelman [1992] to identify measures of effectiveness. In this approach three types of utilisation are distinguished: the knowledge engineer and/or designer applying the knowledge for solving problems, the organisation of designers re-applying the knowledge (in the future) and the customer who is interested in the solutions. The effectiveness of the tool for these users is different but not independent, for example it is obvious that the effectiveness for the customer is dependent on the effectiveness for the other two.

The effectiveness of the SUBCEM prototype is measured by the answers of potential users to a questionnaire which has initially been developed by Adelman [1992]. After a short introduction of each question, the answers of two ship designers are presented. Both designers can be characterised as users familiar with ship design in general, having some experience with conceptual submarine design and the models used within this design stage, but unfamiliar with the design tool. The answers were given after their first experiences with SUBCEM during a two day session. During this session the designers were presented with a submarine design problem along with an operator to act as the interface between them and the tool. The experiences of only two persons cannot be generalised, however the presented approach can be used to evaluate design tools in general.

8.3.1 Match with personnel

The tool and its users interact. If the tool is to be accepted in practice it is important that the users' interaction with the tool is evaluated and adopted when necessary. The implemented knowledge and way of working must be familiar to the users' technical background and working style. The user must be able to understand the models, and its structure between input of design characteristics and output of results. Table 8.12 shows the opinion of the two ship designers about the interaction between them and the tool.

Table 8.12 Opinion of designers about match of tool with personnel

<table>
<thead>
<tr>
<th>SUBCEM user interaction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Match with designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical background</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>general</td>
<td>X&quot;</td>
<td>X&quot;&quot;</td>
<td>specialist</td>
<td></td>
</tr>
<tr>
<td>Work style</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>different</td>
<td>X</td>
<td>equal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operational needs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>not satisfied</td>
<td>X</td>
<td>fulfilled</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1) Problem without adjustments of knowledge base
2) Problem with adjustments of knowledge base

161
Technical background
The technical background of the designer using SUBCEM should be oriented on the overall design process. He or she must have (some) knowledge about all aspects of the design, detailed knowledge about specific design aspects is only required when the implemented knowledge is not sufficient or correct to solve the problem. Understanding the way a design problem is solved is necessary, as each design question might require a different set of questionnaires and input values. For example when a design becomes infeasible, input values must be changed and/or other design models must be incorporated. As long as problems are solved where no new design knowledge must be incorporated, the tool can be used by users with a general technical background on submarine design. If the knowledge must be modified during the solving process, the designer becomes a knowledge engineer who must be much more specialist. This becomes especially valid as the quality and consistency of the knowledge base requires detailed knowledge about the design aspects before the content of the knowledge base can be modified.

Work style
The work style of SUBCEM differs not much from the working style designers traditionally are used to apply during the conceptual design process. However, the possibility to analyse directly the effect of a design decision which is made at the beginning of the sizing process on the performance of the boat, introduces an advanced working style in which more alternatives are analysed before a final decision is made. This possibility of the tool enables the designer to answer a larger number of relevant design questions.

Operational needs
SUBCEM supports the designer’s exploration of a problem by automatically deriving the consequences of the designer’s decisions. The designer formulates its problems and interprets the way the solutions are found. This allows the designer to concentrate on the understanding of the problem (and the solution). The designer learns which values will achieve the design requirements and how much variation of these values can be tolerated, while still achieving acceptable performance. As a result, the designer gains new insights, which ultimately result in the redefinition of the problem. This explorational process can be applied at different levels of detail in the design, enabling to manage the complexity of the problem.

8.3.2 Interface characteristics
The human-tool interface is evaluated by the way the designer operates the tool. An important aspect is the way information is presented to the user. Typical issues are: clarity of questions, explanation of required input values and error handling. Error handling might sometimes require modifications of the design models before results can be obtained. Other aspects are the computational time to calculate results and the possibilities to produce a report for a customer. Table 8.13 shows the opinion of the ship designers about the way they operate SUBCEM.
<table>
<thead>
<tr>
<th>SUBCEM user interaction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interface characteristics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ease of use</td>
<td>complex</td>
<td>X¹</td>
<td>X²</td>
<td>simple</td>
<td></td>
</tr>
<tr>
<td>Ability to modify questionnaire or knowledge</td>
<td>fixed</td>
<td>X</td>
<td>flexible</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Understanding of used terminology</td>
<td>vague</td>
<td>X</td>
<td>clear</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Response time</td>
<td>slow</td>
<td>X</td>
<td>fast</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output of graphs and/or text</td>
<td>none</td>
<td>X</td>
<td>publishable</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1) Solving a new problem
2) Solving an earlier defined problem

Ease of use
The ease of use of SUBCEM is strongly influenced by the type of design questions. The solving strategy of design questions which are often asked, can be stored as macros. These macros reduce the design process for early defined problems to a relative simple task. On the other hand macros become invalid when new knowledge is added or new questions must be solved. For those cases a more complex dialogue must be started. The designer selects during this dialogue knowledge, which is suggested by the tool, for solving the problem or provides input which cannot be determined by the tool. Information during this dialogue about alternative ways to solve the problem is limited. The support is especially limited when a solution cannot be found. For example the tool does not support typical questions such as ‘why could the question not be solved’, or ‘what is the cause of error’, and ‘how should it be solved’ and ‘what must be done to prevent this error in future’.

Ability to modify questionnaire or knowledge
During the dialogue it might be necessary to add new knowledge or to modify existing knowledge before a problem can be solved. Although the tool does not allow these modifications during a dialogue, it does support the adjustment of the knowledge before a dialogue starts. These modifications are taken into account during each new dialogue.

Understanding of used terminology
The ease of use is supported by clear terminology used during the dialogue, as terms are avoided that contain double negative questions, are foreign to the user or are vague defined like: complex, simple etcetera. The quality assurance of the knowledge base guarantees this clarity, as each new design model must be described including practical examples.

Response time
The computational response time of SUBCEM depends on the response time of the knowledge-based system QUAESTOR and the external SUBSPACE programs. As the response time is usually less than a few seconds, the tool is suitable for interactive use. The most computational time consuming process occurs when the non-linear multi-dimensional Newton Raphson method is applied to solve a strong component which contains one or more external programs. This method implies that for each iteration the Jacobian is determined. Computational time can be reduced by using the Quasi Newton
Raphson Method which determines the Jacobian only once during the first iteration or by using the Multiple Newton Raphson Method which determines the Jacobian once after a selected number of iterations. Further, significant computational time might be saved when independent design models (strong components) are solved in parallel instead of sequentially.

**Output**
The results and the way the results are obtained must be reported to the customer. The tool does not support graphical presentation of the results. Output is provided in numerical form and can be visualised by for example spreadsheet programs.

### 8.3.3 Match with organization
Applying the tool has impact on the efficiency and organisational factors of the design corporation. Table 8.14 shows the opinion of the two ship designers about the match between the tool and their design corporation.

<table>
<thead>
<tr>
<th>Table 8.14 Opinion of designers about the match between the tool and their design corporation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SUBCEM - Design corporation</strong></td>
</tr>
<tr>
<td>Efficiency factors</td>
</tr>
<tr>
<td>Match with organizational factors</td>
</tr>
<tr>
<td>Skill requirement</td>
</tr>
<tr>
<td>Effect on conceptual design procedures</td>
</tr>
<tr>
<td>Value in performing other design tasks</td>
</tr>
<tr>
<td>Effect on work load</td>
</tr>
</tbody>
</table>

**Time to accomplish a task and skill requirements**
Efficiency of application depends on time to accomplish a design task. Typically the skills of the designer and the type of design question determine the time required to perform a task. The skills of the designer should be divided into skills for handling the tool and skills for handling the design knowledge. The first type of skills can be obtained by routinely using the tool. The second type of skills depends on the designer's expertise and his understanding of interdependencies among characteristics. The tool supports this understanding by showing how a characteristic effects other characteristics and which other characteristics effect the highlighted characteristic. The modular setup of the knowledge base introduces the possibility to understand the interdependencies of a group of characteristics, for example all relations required to size an object or to determine a performance. However, the tool does not support storage of this chain of relations in a macro when the characteristics are only a part of the total problem, as macros can not be part of other macros. Thus solving a (new) problem requires understanding of the whole design process, which might be a time consuming process. Typically this way of solving a problem is not found in procedural design programs.
Effect on conceptual design procedure
The conceptual design procedure is usually an iterative process in which a solution is adapted until the design fulfills all its required functions. The tool enables the designer to systematically explore object descriptions and to determine the effect on the performance of the boat. The results of these variation studies can show an optimum in a performance, but also the magnitude of the derivative near the optimum.

Value in performing other design tasks
Besides using the tool for optimising a design, it can also be used to determine the performance of existing boats designed by competitors of the design corporation. Especially when new components become available, the design organisation and its competitors want to know the effect of these components on the performance of their (existing) boats.

Effect on work load
The workload to produce a new design is reduced as all data within the design description is consistent or kept consistent when a change is made. However, in search for a better design, more design alternatives are investigated before a decision is made. This increases the workload of the designer to a level which might be equal to or even more than within the usual design procedure.

Knowledge transfer
The purpose of knowledge transfer is to enable the re-use of experience gained during earlier designs. Transparency of the implemented knowledge supports the transfer of knowledge by presenting the structure within the body of knowledge between input of design characteristics and output of results. By building up experience the design process moves from a non-routine design task to a routine design task in which sufficient knowledge is directly available and the way to a solution is known.

8.3.4 Applicability
Coyne defines the Richness of a software tool [Coyne, 1989] by the capability of producing solutions for a range of design questions. Table 8.15 shows the opinion of the two ship designers about the richness of the tool as the capability to solve problems using the implemented knowledge.

<table>
<thead>
<tr>
<th>Table 8.15</th>
<th>Opinion of designers about the Applicability of the tool for the customer</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUBCEM - Customer</td>
<td>1</td>
</tr>
<tr>
<td>Applicability</td>
<td></td>
</tr>
<tr>
<td>Match between knowledge and design problems</td>
<td>none</td>
</tr>
<tr>
<td>Use of answer</td>
<td>none</td>
</tr>
</tbody>
</table>

Match between knowledge and design problems
The match between the implemented knowledge and the design problems in SUBCEM is improved when compared to a totally procedure-based tools, as no specific design
questions are formulated during the implementation of the knowledge. All possible questions can be formulated during the design process, even problem reversing is allowed. To enable problem reversing the in- and output of a limited number of relations must be reversed.

Use of answers
The use of answers in SUBCEM is improved when compared to a totally procedure-based tool as no specific list of results is formulated in advance. All results and the status of the results (input value, initial value, pending value, derived value) are shown during and after the design process.

The answers can be divided depending on the design problem into answers on top-level (results) and on sub-levels (intermediate results).

8.3.5 Robustness
The robustness of the tool depends on the accuracy, stability and completeness of the models implemented in the tool. Table 8.16 shows the opinion of the two ship designers about the robustness of the tool.

<table>
<thead>
<tr>
<th>SUBCEM - customer</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robustness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy of answers</td>
<td>doubt</td>
<td></td>
<td>X</td>
<td>confidence</td>
<td></td>
</tr>
<tr>
<td>Stability of process</td>
<td>unstable</td>
<td></td>
<td>X</td>
<td>stable</td>
<td></td>
</tr>
<tr>
<td>Consistency of results</td>
<td>lacks</td>
<td></td>
<td>X</td>
<td>consistent</td>
<td></td>
</tr>
</tbody>
</table>

Accuracy of answer
The accuracy of the answer depends on the accuracy of the solver and on the accuracy of the implemented models.

The accuracy of the solver becomes important when the model contains strong components which are solved by a non-linear, multi-dimensional Newton-Raphson method. The convergence criterion between two successively obtained solutions is checked at three levels. The first and second level criteria can be influenced by the designer by changing the solver accuracy value. If this value is set too large then the solution might be inaccurate, however if it is set too small the solution process can become less stable. Although a solution might be found which fulfills all convergence criteria, it still can be infeasible as each non-linear model can have multiple solutions and the correct solution is not known in advance. Fortunately, in submarine design most solutions are usually close to the initial values which are stored in the knowledge-base.

The accuracy of the implemented model is different for each design aspect. The validation process during the quality control of SUBCEM assures that the computed solution for a design aspect is sufficiently accurate to serve the purpose for which the model was constructed. The accuracy of some characteristics are dependent on the accuracy of several models in series. For example the accuracy of the prediction of the
centroids of mass and volume of displacement depends on the accuracy of the object sizing models (local centroids) and on the accuracy of the object allocation models (global centroids). The accuracy of characteristics also depend on the purpose of the model. More general applied models are typically less accurate than more specific models. For example, the accuracy of the model which is applied to judge the space utilisation is limited, as this model is made non-specific to eliminate the influence of specific draftsman's creativity at a more detailed design stage than conceptual design.

**Stability of process**
The stability of the design process can be divided into the stability of the solver and the sensitivity of the solution.
The stability of the solver becomes important when convergence cannot be achieved for the model which contains strong components. Many possible errors might have occurred. Typically the following problems occur frequently:

- The solver accuracy value is set too small. This value determines beside the global convergence criterion also the step size and Jacobian in the Newton Raphson method. A too small value can cause a numerical incorrect calculated Jacobian. It might also cause a step size which causes an alternating solution in which each preceding solution is almost equal to the next solution.
- The initial values are not correct. Incorrect initial values might cause non-valid undetermined constraints, which cause removing of relations from the template. Incorrect values also can cause in the first iteration an invalid calculated Jacobian or an invalid starting point for the Newton Raphson method.
- Wrong input given by designer. Wrong input values can cause an invalid calculated Jacobian.

After solving these problems the solver must be restarted, preferably with the initial values as starting values and not the values calculated in the latest (invalid) iteration.

The sensitivity of the solution depends on the implemented design models. A major change in the solution might occur when a small change in the input values causes one or more models to become invalid. The invalid relations are removed from the template and new models must be selected to solve the problem. The new models might produce a different answer, making the solution sensitive for its input values.

**Consistency of results**
A feature of the knowledge-based tool QUAESTOR is its ability to maintain in- and output values consistent. Only when the template contains one or more cycles the values of the characteristics cannot be calculated directly and become pending. Each cycle is solved as soon as it is closed, making all (intermediate) results consistent with their input values. Inconsistency between the input and the (intermediate) results can be introduced when the template contains an indirect recursive function [van Hees, 1997]. This function returns the results of a new dialogue, however after returning the results to the initial template, the template of the new dialogue is destroyed including the intermediate results. Although the designer can change the input values of
characteristics which were required during the new dialogue. Results of the indirect recursive function will not change as its template is destroyed. This inconsistency can be eliminated when the designer re-starts (a part of) the design process which has become inconsistent. The knowledge engineer can support the designer by implementing additional knowledge in the knowledge base by which the inference engine knows which indirect recursive function must be executed after a change is made.

8.4 Conclusions

Evaluating the usability of a design tool is a time-consuming process, but it is a vital part of the tool development as it determines whether it will ever be accepted and used in practice. After the sessions with designers, the value of effectiveness has been discussed. Using these evaluations the strength and weakness of the tool can be better understood. The following points are concluded from this session:

Benefits of the Concept Exploration Model for submarine design implemented in the knowledge-based tool QUAESTOR

- The designer can concentrate on the overall design process, while leaving details to the specialist who has implemented the knowledge.
- Design alternatives caused by different components and/or layouts can be investigated more robustly as the concept exploration model is capable of integrating numerical and spatial aspects of a submarine design.
- The design process is not treated as a search for an optimum, but as an exploration of possibilities which also shows the magnitude of the derivatives near the optimum.
- New knowledge can be added to perform new design tasks, without disrupting the existing knowledge.
- Knowledge transfer is improved as the tool supports the understanding of interdependencies between different models.
- The questions and way to solve design problems during the exploration process can be adjusted, even reversing answer and problem is possible.

Limitations of the Concept Exploration Model for submarine design implemented in the knowledge-based tool QUAESTOR

- Understanding the sequence of design tasks is essential as alternative ways often results into ‘insufficient information available for solving the problem’ as the wrong relations are selected. The tool provides limited (graphical) information about (alternative) ways for solving a problem.
- Implementing knowledge is a time consuming activity as the quality control requires different evaluations before the knowledge base can be released.
- Modifications of the implemented knowledge is not allowed during a dialogue.
- Two reasons limit the re-use of already solved problems: they become invalid when new knowledge is added to the knowledge-base and they can not be part
of other already solved problems.

- Intermediate results of the indirect recursive function(s) are not presented when
  the problem is solved, making the understanding of the final results more
difficult.
- The influence of the designer on the stability of the solver is limited, as one
  solver accuracy value is applied to determine the step size, prediction of the
  Jacobian and checking the convergence criteria when a strong component is
  solved.
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Summary
The research in this thesis has focused on the major development issues which arise during the development of a conceptual design tool. Each step in this process has been examined: identifying the problem, learning about the design-knowledge and its structure, selecting knowledge sources and extracting the knowledge from them, selecting the most promising supporting tools, encoding the knowledge in the tool, verifying, validating the encoded knowledge and evaluating the usability of the encoded knowledge. The development process leading to a conceptual design tool is demonstrated for conceptual design of submarines with a submerged displacement between 1000 - 3000 [ton]. The developed prototype, called SUBCEM, demonstrates the feasibility of a tool for predicting the size and performances of submarines in the conceptual stage of the design process.

Conclusions with respect to the major development issues
Lacking an undirected network and spatial knowledge limits the support of a design tool during the conceptual design of submarines.
From an extensive literature study on design tools supporting the conceptual design stage it is concluded that existing tools show two main limitations. The first limitation arises from the adoption of directed networks, in which the design problem and its way to solve it are fixed. The second limitation arises from the exclusion of geometric and topological knowledge, which disables a description of the internal arrangement. Both are serious limitations for conceptual submarine design. The directed network approach limits problem decomposition, use of various knowledge sources and reformulation of problems. The exclusion of geometric and topological knowledge limits the accurate prediction of the space balance, which is one of the important balances within the submarine design process. The space balance should include at the balances of: volume, area and length.

Variation of design characteristics and calculating performance characteristics offers a convenient way to explore the possible solutions for a design question.
From literature, interviews, existing design programs, history of previous designs and design standards, relevant submarine design knowledge is obtained. It is found that all this knowledge can be broken down according to the three stages in the design process: sizing, balancing and performance calculation. Using a functional decomposition, the design knowledge about each design stage is further systematically classified to less than 100 objects which describe the whole submarine. Five object properties are identified, which must be sized and balanced: weight, space, energy, manning and cost.
The balancing problem checks the viability of the property values. After sizing and balancing the performance characteristics of the submarine are calculated. Although traditionally the design process starts with the question: "what design outcome is required to obtain customer specified performance characteristics?" the approach chosen in the 'run through' case starts with reversing this question to "what are the performance characteristics of the presented design?" as this question can be solved much more (computational) efficiently. The designer can explore the possible solution(s) by variation of the design characteristics such as chosen equipment and layout and calculating the performances of the whole design. However, when the designer decides to follow the traditional design process, SUBCEM can solve the questions asked in that process as well.

Existing design knowledge can provide a good starting point for solving design problems, and should only be improved when its scope, level of detail or level of precision is not sufficient.

Within this research the investigation of the submarine object models is limited to the objects which determine a significant part of the space, weight and energy balance. From existing designs it is concluded that the components fulfilling the floating platform, propulsion, energy supply and life support functions contribute significant to these balances, either on the 'supplying' or on the 'consuming' side. Empirical models and/or models based on physics are developed to determine the individual contributions of the objects to these balances. The scope, level of detail and level of precision of a model is dependent on its 'additional value' for SUBCEM, which is expressed by added functionality, reliability and usability.

The exploration of a design space can be improved by applying a knowledge-based tool in which the design questions are not fixed.

The design task, to be performed by the submarine conceptual design tool, is characterised by exploratory problem solving in which initially design goals are not well defined. During the design process both new questions and new knowledge arise, requiring continuous revision of the initial design problems as the solution evolves. To facilitate this exploratory design process, a number of tool features are defined. To fulfill these features a procedure-based tool is not sufficient; two types of tools must be applied: a knowledge-based tool for numerical knowledge and a procedure-based tool for geometric and topological knowledge. Knowledge-based techniques introduce the un-directed network approach, which enables important tool features like: incremental programming (implementing new design knowledge as soon as it becomes available) and answering different kinds of design questions with the same body of knowledge. The control of the knowledge-based tool is handled by the designer(s), making them responsible for the creativity and the innovation, while leaving the computer to do what it does best: managing large amounts of data. Application of relevant design knowledge and design variables is straight-forward. The knowledge-based tool supports detecting missing information, or invalid information. Even problem reversing is possible using the same set of relations. However, it has also revealed that the use of these tools can give rise to problems. If the designer does not
understand the sequence of design tasks a solution might not be found at all, as parameter(s) can chain to the wrong relation(s). Quality control of the implemented knowledge plays a primary role in avoiding unsolvable problems.

**Current status**

*Case studies have shown the potential of the tool SUBCEM to improve the efficiency of the conceptual submarine design process.*

With the use of the model the submarine design can be analysed in different ways. Case studies have been performed to illustrate that knowledge-based concept exploration is capable of sizing, balancing and calculating the performance of concepts. The outcome of these studies provide a feasible starting point for a more detailed design stage. From the cases, it is concluded that the way in which SUBCEM has been developed leads to a tool which has large potential to improve the efficiency of the conceptual design. Especially when the design problem involves knowledge from different engineering departments, the integrated way of solving the different design aspects reduces the design effort and improves the consistency between the answers. Techniques have been developed to the status where it is possible for the tool to be used by designers. During the development of the tool the role of designer and the role of knowledge engineer were combined into one person. Almost no experience is obtained about the efficiency gain when the designer, does not himself or herself fulfil the role of knowledge engineer. From first experiences can be emphasised that quality control of the body of design knowledge is extremely important when this knowledge must be transferred. It appeared that the knowledge-based tool supports knowledge transfer better than the traditional procedure-based tools, as the formalization of different models into one network provides a basis for obtaining a well-structured body of knowledge.

*The use of the knowledge-based shell QUAESTOR has been an advantage during the development of SUBCEM.*

By using a knowledge-based shell a substantial piece of programming was avoided, enabling the knowledge engineer to focus on the design knowledge and a limited number of special purpose procedure-based programs. A disadvantage of using an existing knowledge-based shell is that the user may not know exactly what has been implemented in the numerical routines. This disadvantage has been overcome by the developer of QUAESTOR by providing in depth information about the programming aspects of the knowledge-based tool. Especially the information about the meta-knowledge, which determines how implemented design knowledge is applied, is essential.

**Future research work**

SUBCEM is still under development, the following extensions will improve the system in practice:

- A number of space and weight characteristics can be defined as object attributes. To increase the accuracy of the spatial models more level of precision should be introduced, e.g. define position of baseline for the local centroid by the designer,
allow non-box shaped objects such as cylinders and spheres and calculate equivalent spaces for each cell instead of for each compartment.

- Implementation of more design models, especially with respect to the energy supply, life support functions and special functions.
- Increase robustness of external procedure-based applications, which are currently acceptable for research applications but might become un-acceptable when they are applied by inexperienced designers.
- More advanced feed-back to the designer by using a graphical interface for showing the size and shape of the net and gross in- and outboard spaces.

The knowledge-based shell QUAESTOR 2.0 is also still under development [van Hees, 1997], the following extensions are proposed to improve the usability of SUBCEM in practice:

- Improving the information about (alternative) ways to solve a problem, to avoid insufficient knowledge for solving the problem.
- Allowing modifications of the implemented knowledge during a dialogue.
- Enabling re-use of solved problems when new knowledge is added to the knowledge-base or when another problem is already solved.
- Presenting and storage of intermediate results of indirect recursive function(s), making the final results better understandable and suitable for modifications.
- Increasing the influence of the designer on the stability of the solver by applying different solver accuracy values for the step size, prediction of the Jacobian and checking the convergence criteria when a strong component is solved.

The insights obtained by this thesis are applicable to many domains in which technical systems can be described by numerical, geometric and topologic information. The attention in this thesis was primarily focussed on Dutch (military) submarines, but due to the separation of the design knowledge and the application, it can easily be adapted to non-military submarines like off-shore inspection vessels, fast pipe-supply vessel [Dijkstra, 1998]. The main limitations encountered are due to the current status of the design models which are implemented for approximating the size and performance of equipment.

The know-how about knowledge acquisition, representation and re-use of design knowledge can be applied in an even wider engineering profession, such as aeroplane design [Rentema, 1998]. In general it is a benefit for each designer to have this know-how and to improve the understanding of the way computers can support him or her most efficiently.
# APPENDIX A SWBS LIST

This appendix contains the object list as applied in the SUBCEM project. Within this list distinction is made between objects which properties are determined by models (in bold), or which properties have constant (default) values (in italics), or which property values are combined with other objects.

<table>
<thead>
<tr>
<th>FUNCTION</th>
<th>OBJECTS</th>
<th>Obj</th>
<th>Abbr.</th>
<th>COMPONENTS</th>
<th>SWBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrying platform</td>
<td>Cyl Press Hull</td>
<td>111</td>
<td>PH</td>
<td>Pressure hull shell</td>
<td>1111</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>hull penetrations</td>
<td>1114</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Structural forgings and equivalent weldings</td>
<td>1610</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hull insulation</td>
<td>6350</td>
</tr>
<tr>
<td>Bulkheads</td>
<td>112</td>
<td>BulkH</td>
<td></td>
<td>Pressure hull heads</td>
<td>1112</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Longitudinal structural bulkheads</td>
<td>1210</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Transverse structural bulkheads</td>
<td>1221</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Transverse gas-tight bulkheads</td>
<td>1222</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Transverse bulkhead</td>
<td>1223</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Non structural bulkheads</td>
<td>6210</td>
</tr>
<tr>
<td>Tanks</td>
<td>113</td>
<td>HTank</td>
<td></td>
<td>Hard tanks</td>
<td>1250</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Soft tanks</td>
<td>1260</td>
</tr>
<tr>
<td>Trunks Enclosure</td>
<td>114</td>
<td>Trunks</td>
<td></td>
<td>Conning tower</td>
<td>1113</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Trunks, WT/GT doors, hatches</td>
<td>1230</td>
</tr>
<tr>
<td>Hull</td>
<td>121</td>
<td>Hull</td>
<td></td>
<td>Outer hull shell</td>
<td>1121</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Added hull shell</td>
<td>1511</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hull structure foundations</td>
<td>1810</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rails, stanchions and lifelines</td>
<td>6120</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rigging</td>
<td>6130</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cathodic protection</td>
<td>6331</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Anti fouling systems</td>
<td>6332</td>
</tr>
<tr>
<td>Appendages</td>
<td>123</td>
<td>App</td>
<td></td>
<td>Shell appendages (incl. skegs)</td>
<td>1140</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sail</td>
<td>1512</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rudder/diving planes forward and aft</td>
<td>5661</td>
</tr>
<tr>
<td>Decks</td>
<td>124</td>
<td>Decks</td>
<td></td>
<td>Main decks</td>
<td>1310</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Platforms</td>
<td>1410</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Deck covering</td>
<td>6340</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Floor plates and grating</td>
<td>6220</td>
</tr>
<tr>
<td>StructAuxiliary</td>
<td>125</td>
<td>StrucAux</td>
<td></td>
<td>Painting</td>
<td>6310</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ladders</td>
<td>6230</td>
</tr>
<tr>
<td>Part</td>
<td>Code</td>
<td>Description</td>
<td>Model No.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
<td>------</td>
<td>--------------------------------------------------</td>
<td>-----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Margin Ballast</td>
<td>191</td>
<td>MBallast</td>
<td>M110, M350</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stability Ballast</td>
<td>192</td>
<td>SBallast</td>
<td>1910</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Manoeuvring</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Elect Motor</td>
<td>211</td>
<td>MEM</td>
<td>2351</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEM Auxiliaries</td>
<td>212</td>
<td>MEMaux</td>
<td>1821, 2355, 2353, 2521</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mech Transmission</td>
<td>221</td>
<td>MTrans</td>
<td>2421, 2431, 2432, 2441, 2442, 1820</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propeller</td>
<td>231</td>
<td>Prop</td>
<td>2451</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluid Ship Handf</td>
<td>241</td>
<td>FShpHdl</td>
<td>5641, 5642, 5291, 5513, 5521, 5541, 5630</td>
<td></td>
<td></td>
</tr>
<tr>
<td>control surfaces</td>
<td>242</td>
<td>Planes</td>
<td>5611, 5662</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SeaWater Tanks</td>
<td>243</td>
<td>SWTank</td>
<td>F711, F721</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mech Ship Handl</td>
<td>251</td>
<td>MSmphHdl</td>
<td>5610, 5620</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Energy supply</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batteries</td>
<td>311</td>
<td>Batt</td>
<td>2231</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery Aux</td>
<td>312</td>
<td>BattAux</td>
<td>1830, 2222</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Design and building margins**
- **Future growth margin**
- **Bast (fixed)**
- **Main electric motor (incl. mounting system)**
- **Seatings M.E.M**
- **Choppers**
- **Propulsion power supply system**
- **Propulsion control system**
- **Couplings**
- **Shafting**
- **Shaft Sealing**
- **Shaft bearings**
- **Thrustblock**
- **Seatings Thrustblock**
- **Propeller**
- **Trim system**
- **Weight compensation system**
- **Bilge system**
- **HP air blowing system**
- **Gas generator system**
- **Ballasting & deballasting system MBT's**
- **Hovering and depth control in 5541**
- **Steering/diving actuators forward and aft**
- **Rudder/diving plane lubricating equipment**
- **Main ballast water**
- **Weight compensation water**
- **Trim water**
- **Anchor handling and slownage system**
- **Mooring and towline system**
- **Battery cooling water system**
- **Distilled water system**
- **Battery agitation system**
- **Battery monitoring system**
- **Hydrogen detecting equipment**
- **HZ elimination system**
- **Cell lifting and transport equipment**
- **Battery compartment ventilation**
- **Distilled water**
<table>
<thead>
<tr>
<th>Tankage fuel</th>
<th>FOtank</th>
<th>Fuel F76</th>
<th>F451</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator Set</td>
<td>321 DG</td>
<td>Diesel engines (incl. mounting system) 2331</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diesel engine start stop system 2522</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Generators 2332</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Propulsion plant foundations 1820</td>
<td></td>
</tr>
<tr>
<td>Diesel Eng Fluids</td>
<td>322 DEfluid</td>
<td>Lube oil system diesel engine 2333</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fresh water cooling system diesel engine 2334</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diesel sea water cooling system 2561</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fuel oil service and conditioning system 2611</td>
<td></td>
</tr>
<tr>
<td>Diesel Eng Gas</td>
<td>323 DEgas</td>
<td>Starting air system diesel engine 2335</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Air intake system 2511</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gas exhaust system 2591</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water in snorting tank F732</td>
<td></td>
</tr>
<tr>
<td>Conv DC-AC</td>
<td>324 DC-AC</td>
<td>440V @ 60 Hz conversion system 3142</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>115V @ 60 Hz conversion system 3143</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>115V @ 400 Hz conversion system 3144</td>
<td></td>
</tr>
<tr>
<td>Conv DC-Hyd</td>
<td>325 DC-Hyd</td>
<td>Hydraulic oil plant 5561</td>
<td></td>
</tr>
<tr>
<td>Conv DC-HP</td>
<td>326 DC-HP</td>
<td>HP air plant 5511</td>
<td></td>
</tr>
<tr>
<td>Conv DC-Chilled</td>
<td>327 DC-Chill</td>
<td>Chilled plant/unit 5142</td>
<td></td>
</tr>
<tr>
<td>Conv DC-DC</td>
<td>328 DC-DC</td>
<td>24V batteries, charging equipment 3131</td>
<td></td>
</tr>
<tr>
<td>Closed Cycle</td>
<td>329 CCDE</td>
<td>Closed cycle diesel engine (CCDE) 2381</td>
<td></td>
</tr>
<tr>
<td>Diesel Engine</td>
<td></td>
<td>Generator for CCDE 2382</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lube oil system CCDE 2383</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fresh water cooling system CCDE 2384</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Starting air system CCDE 2385</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CCDE control systems 2523</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CCDE sea water system 2562</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CCDE gas recycling system 2592</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oxygen supply system 2711</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Argon supply system 2712</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reference air supply system 2713</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reference air storage system (CCDE) 5522</td>
<td></td>
</tr>
<tr>
<td>E-Distr local</td>
<td>331 EdistrLo</td>
<td>DC power distribution system 3241</td>
<td></td>
</tr>
<tr>
<td>E-Distr global</td>
<td>332 EdistrGl</td>
<td>Cable tray, glands, connectors &amp; cables 3212</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>440V @ 60 Hz power distribution system 3242</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>115V @ 60 Hz power distribution system 3243</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>115V @ 400 Hz power distribution system 3244</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>24V DC power distribution system 3245</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>General, orientation and adaptive lighting 3311</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Emergency lighting system 3312</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Auxiliary lighting system 3313</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Operational lighting system 3314</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lighting fixtures: in 3310</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Equalizing ventilation 5121</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Air conditioning systems 5141</td>
<td></td>
</tr>
<tr>
<td>Category</td>
<td>Code</td>
<td>Description</td>
<td>Code</td>
</tr>
<tr>
<td>---------------------</td>
<td>------</td>
<td>-------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Hydr Oil tankage</td>
<td>341</td>
<td>HOtank</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydraulic oil h546</td>
<td>F541</td>
</tr>
<tr>
<td>Lube Oil tankage</td>
<td>342</td>
<td>LOtank</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lube oil 0240</td>
<td>F461</td>
</tr>
<tr>
<td>Tankage CCDE</td>
<td>343</td>
<td>CCDETank</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Liquid oxygen storage and transfer systems</td>
<td>5531</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nitrogen storage system</td>
<td>5532</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Argon storage and transfer system</td>
<td>5533</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Liquid oxygen</td>
<td>F591</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Argon</td>
<td>F563</td>
</tr>
<tr>
<td>Ship control</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>411</td>
<td>ShipCont                                            5612</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Automatic steering/depth control system</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Includes rudder angle measuring system</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Integrated platform control and monitoring system</td>
<td>4381</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control centre furnishings</td>
<td>6620</td>
</tr>
<tr>
<td>Navigation/Observation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Navigat Proc</td>
<td>511</td>
<td>NavP</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Navigation inventory</td>
<td>4211</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Satellite navigation system: GPS NAVSTAR</td>
<td>4231</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radio navigation syst.: OMEGA/DECCALORAN-C</td>
<td>4232</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Echosounder</td>
<td>4241</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compass, log, Depth, Clock, Angle-system</td>
<td>4260</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sins in 4260</td>
<td>4271</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chart table</td>
<td>4281</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Chart table panel</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Automatic plot table</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data retransmission system</td>
<td>4282</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Data retransmission unit</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Repeaters</td>
<td></td>
</tr>
<tr>
<td>Ext Obsv Sensors</td>
<td>512</td>
<td>ExtObsS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Active sonar (AS)</td>
<td>4611</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cylindrical array sonar (CAS)</td>
<td>4621</td>
</tr>
<tr>
<td>Communication</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Int Comm Process</td>
<td>611</td>
<td>IntComm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Automatic dial telephone system</td>
<td>4321</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sound powered telephone system</td>
<td>4322</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Internal communication system</td>
<td>4331</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Engine room announcing system</td>
<td>4332</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WT hatches warning system</td>
<td>4361</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fire detection system</td>
<td>4363</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diving alarm system</td>
<td>4364</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radiac system</td>
<td>4365</td>
</tr>
<tr>
<td>Ext Comm Process</td>
<td>612</td>
<td>ExtCommP</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>VHF, UHF radio system</td>
<td>4412</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radio distribution and switching</td>
<td>4311</td>
</tr>
<tr>
<td>Category</td>
<td>Code</td>
<td>Description</td>
<td>Code</td>
</tr>
<tr>
<td>---------------------</td>
<td>------</td>
<td>--------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Salcom system</td>
<td></td>
<td></td>
<td>4414</td>
</tr>
<tr>
<td>Underwater telephone system</td>
<td></td>
<td></td>
<td>4421</td>
</tr>
<tr>
<td>Emergency underwater telephone system</td>
<td></td>
<td></td>
<td>4422</td>
</tr>
<tr>
<td>Ext Comm Sensors</td>
<td>621</td>
<td>ExtCommS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Navigation lights</td>
<td>4221</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Signal identification lights</td>
<td>4431</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Signal horn</td>
<td>4432</td>
</tr>
<tr>
<td>Life support</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Life Supp Distr</td>
<td>711</td>
<td>LSdist</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>General entertainment system</td>
<td>4341</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compartment heating system</td>
<td>5110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Air analyzing system</td>
<td>5154</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sanitary flushing system</td>
<td>5211</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Domestic fresh and hot water system</td>
<td>5331</td>
</tr>
<tr>
<td>Life Supp Proces</td>
<td>712</td>
<td>LSproces</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>O2 generation system</td>
<td>5153</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO2 absorption system</td>
<td>5151</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fresh water generating system</td>
<td>5331</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sewage system</td>
<td>5931</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Garbage ejector system</td>
<td>5932</td>
</tr>
<tr>
<td>Pers Life Saving</td>
<td>721</td>
<td>PerSav</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Portable fire extinguishers</td>
<td>5552</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BIBS/HIS system</td>
<td>5941</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Escape trunk flood/drain system: in 5941</td>
<td>5942</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Life saving appliances</td>
<td>5945</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SSE grenades</td>
<td>F326</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Life saving equipment</td>
<td>F327</td>
</tr>
<tr>
<td>Gen life Saving</td>
<td>722</td>
<td>GenSav</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Halon fire extinguishing system</td>
<td>5551</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Underwater signal ejectors</td>
<td>5551</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Marker buoy system</td>
<td>5943</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Beacon set.DSRV</td>
<td>5944</td>
</tr>
<tr>
<td>Accommodation</td>
<td>731</td>
<td>Accom</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Outfit and furnishing foundations</td>
<td>1860</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cabin doors</td>
<td>6241</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sheating (incl. Lining)</td>
<td>6370</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Officer berthing and messing spaces</td>
<td>6410</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non commissioned off berthing and mess</td>
<td>6420</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Enlisted personnel berthing and mess</td>
<td>6430</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sanitary spaces and fixtures</td>
<td>6440</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Galley</td>
<td>6511</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Workshops (incl. portable tools, equipment)</td>
<td>6650</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inventory</td>
<td>F323</td>
</tr>
<tr>
<td>Provisions</td>
<td>741</td>
<td>Prov</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Domestic cool and cold stores</td>
<td>5161</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ship stores and equipment handling system</td>
<td>5720</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medical provisions</td>
<td>6521</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lockers and special stowage</td>
<td>6710</td>
</tr>
<tr>
<td></td>
<td></td>
<td>General stowage facilities</td>
<td>6721</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO2 absorption material</td>
<td>F324</td>
</tr>
<tr>
<td></td>
<td></td>
<td>O2 candles</td>
<td>F325</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Storerooms' contents</td>
<td>F321</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Provisions in cool stores</td>
<td>F311</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Provisions in cold stores</td>
<td>F312</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Provisions in other stores (incl. Galley)</td>
<td>F314</td>
</tr>
<tr>
<td>Crew</td>
<td>751</td>
<td>Crew</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Officers</td>
<td>F111</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Officers' luggage</td>
<td>F112</td>
</tr>
<tr>
<td>Category</td>
<td>Code</td>
<td>Description</td>
<td>Code</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>------</td>
<td>--------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Special (military) functions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black water</td>
<td>761</td>
<td>BW</td>
<td>F551</td>
</tr>
<tr>
<td>Fresh water</td>
<td>762</td>
<td>FW</td>
<td>F521</td>
</tr>
<tr>
<td>Masts &amp; Periscopes</td>
<td>811</td>
<td>Masts</td>
<td></td>
</tr>
<tr>
<td>Surface search radar</td>
<td>4511</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Periscope</td>
<td>4251</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optronic system</td>
<td>4252</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Submarine masts (Combat System)</td>
<td>4001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elevating and retracting gear of masts/ periscopes/ fairings</td>
<td>5850</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic blocks for actuating cylinders</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mil Data Process</td>
<td>821</td>
<td>MDaLP</td>
<td></td>
</tr>
<tr>
<td>Data display system</td>
<td>4111</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tactical data handling system</td>
<td>4121</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interface equipment (P. M.)</td>
<td>4140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data communication system</td>
<td>4151</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Underwater noise level monitoring system</td>
<td>4371</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavitation monitoring system</td>
<td>4372</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VLF, HF radio system</td>
<td>4411</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Link 11 system</td>
<td>4413</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Telemetry systems</td>
<td>4440</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Teletype system</td>
<td>4451</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crypto system</td>
<td>4461</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IFF transponder system</td>
<td>4551</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental prediction and monitoring system</td>
<td>4651</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESM system</td>
<td>4721</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EW ESM system</td>
<td>4722</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Command and surveillance operating fluids</td>
<td>4980</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Command and surveillance repair parts and special tools</td>
<td>4990</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Command and surveillance foundations</td>
<td>1840</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mil Sonars</td>
<td>831</td>
<td>MSonar</td>
<td></td>
</tr>
<tr>
<td>Mine avoidance sonar (MAS)</td>
<td>4612</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flank array sonar (FAS)</td>
<td>4622</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passive ranging sonar (PRS)</td>
<td>4623</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept sonar (IS)</td>
<td>4624</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Towed array sonar (TAS)</td>
<td>4625</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passive sonar analysis and class system (PSAC)</td>
<td>4626</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple mode sonar</td>
<td>4630</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Classification sonar</td>
<td>4640</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clip-on assembly towed array</td>
<td>5952</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large weapons</td>
<td>841</td>
<td>Lwep</td>
<td></td>
</tr>
<tr>
<td>Torpedoes</td>
<td>F211</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wire dispensers</td>
<td>F213</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Missiles</td>
<td>F212</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mines (P. M.)</td>
<td>F214</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weapon embarkation system</td>
<td>7521</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Category</td>
<td>Code</td>
<td>Subcategory</td>
<td>Item Description</td>
</tr>
<tr>
<td>-------------------</td>
<td>------</td>
<td>----------------------</td>
<td>-----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Weapon stowage, shifting and reloading system</td>
<td>7531</td>
<td>Small weapons</td>
<td>842 Swap</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Small arms</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Destruct charges</td>
</tr>
<tr>
<td>Weapon reloading system: in 7531</td>
<td>7522</td>
<td>Weapons Aux</td>
<td>843 WeapAux</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Torpedo decoys</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Decoys (other)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Encapsulated harpoon control and launching system</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Torpedo fuel pollution control system</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Weapon control system</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Electronic test, checkout and monitoring equipment</td>
</tr>
<tr>
<td>Torpedo tubes</td>
<td>7511</td>
<td>Torpedo Tubes</td>
<td>844 tubes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Torpedo tubes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bow caps and operating gear</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Torpedo tube - blowvent. and flood drain system</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Torpedo tube - holding &amp; firing air system</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Torpedo ejection: in 7514</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Torpedo tube - hydraulic oil system</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td></td>
<td>Operating Fluids</td>
<td>911 OpFluids</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Free flooding liquids</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Propulsion plant operating fluids</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Auxiliary systems operating fluids</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Torpedo systems operating fluids</td>
</tr>
<tr>
<td>Spare Parts Tools</td>
<td>7990</td>
<td>SpareParts Tools</td>
<td>921 Parts</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hull repair parts and special tools</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Propulsion plant repair parts and special tools</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Electric plant repair parts and special tools</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Auxiliary systems repair parts and special tools</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Outfit and furnishing repair parts and special tools</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Torpedo systems repair parts and special tools</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spare parts</td>
</tr>
<tr>
<td>Air</td>
<td>F561</td>
<td>Air</td>
<td>931 Service space bew. objects</td>
</tr>
<tr>
<td></td>
<td>4611</td>
<td></td>
<td>Active sonar (AS)</td>
</tr>
<tr>
<td></td>
<td>4621</td>
<td></td>
<td>Cylindrical array sonar (CAS)</td>
</tr>
</tbody>
</table>
APPENDIX B MAIN ELECTRIC MOTOR SIZING MODEL

This appendix presents a model for sizing a direct current Main Electric Motor (MEM). The purpose of this model is to calculate the required space properties of a direct current, compound excited, non-compensated (armature winding field) electric motor.

Quality control of the development involves evaluating the 'value' of the capabilities of a model before it is implemented. For the SUBCEM project the quality characteristics in table B.1 can be used to measure the value of the additional capability. Other quality characteristics like efficiency become important when the product is applied in a design office. All decisions during the development process should be made after evaluation of the three quality characteristics, which means that the value of each proposal for an improvement must be identified.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Description</th>
<th>High level</th>
<th>Low level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality</td>
<td>The importance of the function</td>
<td>Vital</td>
<td>Unimportant</td>
</tr>
<tr>
<td>Reliability</td>
<td>The validity of the results</td>
<td>Valid</td>
<td>False</td>
</tr>
<tr>
<td>Usability</td>
<td>The ability of predicting a value</td>
<td>Novel</td>
<td>Existing</td>
</tr>
</tbody>
</table>

The quality control of the development process requires evaluation of the 'additional value' of the MEM sizing model for SUBCEM:

Adding functionality
The functionality of the system improves:
- The MEM is a vital system for fulfilling the propulsion driving function of the submarine.

Adding reliability
The reliability of the system improves:
- The prediction of the required space for the MEM improves. This improves the system as the space size of the MEM is large compared to the size of the compartment to which it is allocated.

Adding usability
The usability of the system improves:
- The MEM is a product which is specially designed or modified for each type of submarine, as its requirements are dependent on the required propulsion performance of the submarine.
As the MEM sizing model adds 'value' to the SUBCEM, a knowledge elicitation process is started by Deleroi [1994] and refined by Pel [1995a] to obtain a numerical model. A summary of the results of this elicitation is described in the following paragraphs.

B.1 Design requirements MEM

The purpose of the MEM is to convert efficiently Direct Current energy into mechanical energy. Two design conditions are defined for the MEM: a burst and a maximum continuous condition. The burst condition defines the maximum power and associated rotation rate. This condition determines the maximum allowable mechanical and magnetic load, while the maximum allowable thermal load may be exceeded. The maximum continuous condition defines the maximum allowable thermal load.

B.2 The components of the MEM

Figure B.1 shows the longitudinal and cross sectional view of a MEM [Deleroi, 1994]. Sizing the MEM consists of sizing the components from which the MEM is built. The two main components are the motor and the cooling system. The motor can be further divided into the static and the rotary components. The size dominant static components are the housing, stator yoke, main poles and interpoles. The size dominant rotary components are the rotor, shaft and commutator.

Figure B-1 Main Electric Motor

184
B.3 The MEM space sizing model

The purpose of the MEM sizing model is to determine the space properties of the MEM. The space properties contain width, length, height, area and volume which is required to allocate the MEM to a space. Sizing of components which are required in the MEM performance models are not presented here.

MEM width calculation

Assumption: The MEM width is equal to Motor diameter

Motor diameter is determined by the geometry and topology of the components, represented by a function:

$$D_{mot} = D_a + 2.\, h_p + 2.\, \delta + 2.\, h_y$$

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{mot}$</td>
<td>Motor diameter</td>
<td>[m]</td>
</tr>
<tr>
<td>$D_a$</td>
<td>Diameter rotor</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_p$</td>
<td>Pole height</td>
<td>[m]</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Air gap thickness</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_y$</td>
<td>Height of the stator yoke</td>
<td>[m]</td>
</tr>
</tbody>
</table>

Diameter rotor

To calculate the rotor diameter, its armature winding is divided into a finite number of conductors. For each conductor the 2nd law of Maxwell is applied to determine the electromotive force. The flux density used in this law is determined using Faraday’s principle and the observation that within a magnetic circuit no flux can be lost. Using these first principles and geometric knowledge about DC motor design, the rotor diameter is calculated by the equation:

$$D_a = \sqrt[3]{\left( \frac{P_B}{n_{revburst} \, Z_a} \right)^{\frac{3}{4}} \frac{4\, p}{n_{MEM} \, n^3 \, \alpha \, J_a \, k_{CU,a} \, h_N \, B_o}}$$

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_B$</td>
<td>Brake power in burst condition</td>
<td>[kW]</td>
<td>INPUT</td>
</tr>
<tr>
<td>$n_{revburst}$</td>
<td>Rotation rate in burst condition</td>
<td>[1/min]</td>
<td>INPUT</td>
</tr>
<tr>
<td>$Z_a$</td>
<td>Number of armatures</td>
<td>[-]</td>
<td>INPUT</td>
</tr>
<tr>
<td>$p$</td>
<td>Number of pole pairs</td>
<td>[-]</td>
<td></td>
</tr>
<tr>
<td>$n_{MEM}$</td>
<td>Efficiency MEM</td>
<td>[-]</td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Ratio active copper area of pole and total pole area</td>
<td>[-]</td>
<td>Technological constant</td>
</tr>
<tr>
<td>$J_a$</td>
<td>Armature current density</td>
<td>[A/m²]</td>
<td>Technological constant</td>
</tr>
<tr>
<td>$k_{CU,a}$</td>
<td>Armature winding space factor in slots</td>
<td>[-]</td>
<td>Technological constant</td>
</tr>
<tr>
<td>$h_a$</td>
<td>Height of armature slot</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td>$B_a$</td>
<td>Air gap induction</td>
<td>[T]</td>
<td></td>
</tr>
</tbody>
</table>

To derive this equation the following assumptions are made:

Assumption: Gap flux density is constant along the pole face area.

Assumption: Ratio between rotor teeth-width and slot width is equal to one.

Assumption: Effective iron length of the conductor is equal to peripheral length of pole pitch.

The result of this relation is only allowed when following restriction is met:
Restriction: Circumferential speed of rotor is smaller than 25 [m/s], to limit the radial forces on the armature windings.

The number of pole pairs and the height of the armature slot are determined from geometric knowledge about DC motor design, presented by Deleroi [1993]. The number of pole pairs is a discrete number, this results in a stepwise function of the number of pole pairs depending on the rotor diameter. The armature slot height is also a function of the rotor diameter. The slot height function reaches a maximum value due to the limited thickness of the rotor structure. As both parameters are related to the rotor diameter, cycles are created in the model.

The efficiency of the MEM is determined from the load losses. These losses can be calculated when the dimensions of the components are determined. As the dimensions are unknown, another cycle is created in the model. The losses consist of: iron losses, pole shoe losses, brush losses, Joulean excitation losses, Joulean armature, -interpole, -brush losses, chopper losses and bearing friction losses. Details about these models can be found in Pel [1995a].

The relation which calculated the rotor diameter is also shown in table B.2 at end of this appendix. This table is an example of a page in the so-called knowledge dictionary [Durkin, 1994]. The knowledge dictionary of SUBCEM contains all numerical knowledge, including its control knowledge. During the evaluation of the knowledge coding [Adelman, 1992] the knowledge dictionary is valuable, as it provides a detailed overview (and history) of all implemented knowledge.

Pole height
To calculate the pole height the cross sectional area available between rotor and stator yoke must be equal to the area required for the poles, interpoles, their windings and cooling air. The Pole winding area can be calculated using the observation that the magnetic field along peripheral length of the pole shoe must be in motor operation. This magnetic field is equal to the resultant of the magnetic field generated on one hand by the field windings and on the other hand by the armature windings. Figure B.2 shows a simplified drawing of both fields.

![Diagram of magnetic fields](image)

Figure B.2  Magnetic field generated by the field and armature windings

To fulfill this observation the induction generated by the two field windings of a pole pair is
taken equal to the induction generated by the armature windings below the active area of each pole. Both inductions are calculated using the 1st law of Maxwell. The dimensions of the other components are calculated using geometric knowledge about DC motor design. Using these first principles and geometric knowledge about DC motor design, the pole height is obtained by the solution of the second order equation:

\[
h_p^2 \left[ \frac{\pi \cdot k_1}{4 \cdot p} \right] + h_p \left[ \frac{\pi \cdot k_1}{4 \cdot p} \cdot (D_a + 2 \cdot \delta) - \left( \frac{B_b}{B_p} \right) \cdot \frac{k_{st} \cdot \alpha \cdot D_a \cdot \pi}{4 \cdot p} - \frac{\pi \cdot D_a}{K_x} \right] + \\
\left[ \frac{-k_{Cu,a}}{K_{v,p}} \cdot \frac{J_a}{J_w} \cdot \frac{h_n \cdot D_a \cdot \pi}{8 \cdot p} - \frac{B_b \cdot \delta}{\mu_0 \cdot k_{v,p} \cdot J_w} \right] = 0
\]

\[h_p\] Pole height \[B_p\] Pole induction \[k_1\] Air factor of stator yoke \[k_{st}\] Stray factor \[K_x\] Number of commutator bars \[K_{v,p}\] Space factor of stator winding \[J_a\] Stator winding current density \[\mu_0\] Field magnetic permeability

To derive this equation the following assumptions are made:

**Assumption:** Width interpole is equal to slot pitch.

**Assumption:** Amount of copper in the interpoles is equal to amount of copper in the armature.

**Assumption:** Number of armature slots is half the number of commutator bars

The number of commutator bars is calculated from the maximum terminal voltage and the maximum allowable voltage between the bars to avoid ionization of the air.

**Air gap thickness**

Using a technological based value for the air gap induction, the effective air gap thickness can be calculated using Maxwell's 1st law. The field in the airgap is larger than in the iron of the magnetic circuit generated by the field windings is determined, as the field magnetic permeability of iron is much larger than the value for air. Using this observation and the above made observation, in which the field generated by the field windings is assumed to be equal to the field generated by the armature windings, then the air gap thickness can be calculated by the function:

\[
\delta = \frac{\mu_0 \cdot J_a \cdot h_n \cdot \pi \cdot D_a \cdot \alpha \cdot k_{Cu,a}}{8 \cdot p \cdot B_b}
\]

**Height of the stator yoke**

To calculate the stator yoke height is calculated using the observation that within a magnetic circuit no flux can be lost.
\[ h_{sj} = \left( \frac{B_s}{B_{sj}} \right) \cdot \frac{(\tau_p \cdot \alpha)}{2} \cdot \frac{k_{st}}{k_{sj}} \]

- \( \tau_p \): Peripheral length of the pole pitch \([\text{m}]\)
- \( B_s \): Stator yoke induction \([\text{T}]\)
- \( k_{st} \): Stator yoke length correction \([\text{r}]\)
- \( k_{sj} \): Technological constant

The peripheral length of the pole pitch is calculated from the geometry of the stator and the number of pole pairs.

\[ \tau_p = \frac{D_a \cdot \pi}{2 \cdot p} \]

MEM length calculation

The length of the MEM includes the length of radial/axial bearings, rotors, collectors. From geometric knowledge about DC motor design an additional length is observed between armatures, a so-called air gap between armatures.

The length of the flange is not included in this calculation, as the width and height of the MEM are not required at the cross section of the flange. The flange is either another object or a part of the object “mechanical energy transmission”.

\[ l_{\text{mot}} = l_{\text{bear}} + Z_a \cdot \left( l_{\text{rot}} + l_k + l_{\text{airgap}} \right) \]

- \( l_{\text{mot}} \): MEM length \([\text{m}]\)
- \( l_{\text{bear}} \): length of bearing \([\text{m}]\)
- \( l_{\text{rot}} \): rotor length \([\text{m}]\)
- \( l_k \): collector length \([\text{m}]\)
- \( l_{\text{airgap}} \): length of the airgap between armatures \([\text{m}]\)

Bearing length

The bearing length is equal to the length of a radial and a radial/axial shaft bearing. From geometric knowledge about DC motor design is observed that the length is related to the shaft diameter at the coupling to the rotor.

\[ l_{\text{bear}} = 2 \cdot \sqrt[3]{\frac{2 \cdot P_B}{n \cdot \mu \cdot \pi \cdot \sigma_0} + 1} \]

- \( \sigma_0 \): Radial surface pressure \([\text{N/mm}^2]\)
- \( l_{\text{sa}} \): Additional length of axial- relative to radial bearing \([\text{m}]\)
- \( \mu \): Coefficient of friction \([-]\)
- \( P_B \): Technological constant
- \( n \): Technological constant
- \( \sigma_0 \): Technological constant

**Assumption:** For low rotation speed requirements is the ratio between radial bearing length and shaft diameter is equal to one.

**Assumption:** The shaft is coupled to the rotor with an interference fit. The length of this fit equals the diameter of the shaft.

**Assumption:** The length the axial bearing is equivalent to the length the radial bearing plus an additional length.

188
Rotor length
From geometric knowledge about DC motor design is observed that the rotor length of one armature is dependent on the effective iron length and the winding head length.

\[ l_{\text{rot}} = (1 + k_{ls}) \cdot r_p \]

- \( k_{ls} \): Air factor of rotor yoke
- \( r_p \): Technological constant

**Assumption:** The winding head length is half the length of the pole pitch [Deleroi, 1993]

**Assumption:** The effective iron length is equal to the pole pitch

Collector length
The length of the collector depends on the maximum current through the armature per pole pair, the dimensions of a brush and its maximum allowable brush current density.

\[ l_k = \frac{I_0}{J_b \cdot p \cdot l_b \cdot b_b} \cdot (l_b + l_{ab}) + l_z \]

- \( J_b \): Brush current density
- \( I_0 \): Maximum current through armature
- \( l_b \): Brush length
- \( b_b \): Brush breadth
- \( l_z \): Additional safety length of the commutator
- \( l_{ab} \): Brush distance in longitudinal direction

- \([\text{A/m}^2]\): Technological constant
- \([\text{A}]\): Technological constant
- \([\text{m}]\): Technological constant
- \([\text{m}]\): Technological constant

Air gap length
From geometric knowledge about DC motor design is observed that the air gap length is equal to half the length of the winding head length.

MEM Height calculation
The height of the MEM includes the height of the motor plus the height of the cooler.

\[ h_{\text{MEM}} = d_{\text{mot}} + h_{\text{cool}} \]

- \( h_{\text{MEM}} \): Height MEM
- \( h_{\text{cool}} \): Height Cooler MEM

**Assumption:** The air-cooler of the MEM is located above the motor.

**Assumption:** The shaft of the MEM is at the same height as the centre line of the submarine.

Height of the cooler
The cooling system includes per armature a cooler, two fans and a filter unit. From geometric knowledge about DC motor design is observed that tubular air to water coolers are applied, in which the distance between the pipes and the distance between the fins at the air side are
technological constants. Knowing the cross sectional area of the cooler, the number of cooling pipes in axial direction can be calculated using the required cooling surface. The required cooling surface is determined from the equation:

\[ P_{loss_{cool}} = k \cdot \Delta \theta \cdot A_{cool} \]

- \( P_{loss_{cool}} \): heat losses to cooler during max. continuous cond. [W]
- \( \Delta \theta \): logarithmic decrement of the cooler temperatures [K]
- \( k \): heat transmission coefficient [W/m²K]
- \( A_{cool} \): cooling surface [m²]

To calculate the logarithmic decrement of the cooler the following assumptions are made:

**Assumption:** 90% of the MEM heat production is transmitted to cooler, the remaining 10% to the environment by radiation.

**Assumption:** Maximum temperature air inlet dependent on the maximum allowable temperature of the insulation material between the windings.

**Assumption:** Temperature difference air side of cooler at maximum continuous condition is a technological constant.

**Assumption:** Temperature difference cooling water side of cooler at maximum continuous condition is a technological constant.

Figure B.3 shows a typical cooler for the MEM [Pel, 1995a]. The total cooling surface is calculated by:

\[ A_{cool} = \pi \cdot d_{pipe} \cdot b_{cool} \cdot \frac{h_{cool}}{s_1} \cdot \frac{l_{cool}}{s_2} \]

- \( d \): diameter cooling pipe [m]
- \( s_1 \): centre line dist. of cooling pipes in vertical plane [m]
- \( s_2 \): centre line dist. of cooling pipes in horizontal plane [m]

Figure B.3 Typical MEM cooler (water-air)

The cross sectional area of the cooler is dependent on the maximum cooling air velocity through the cooler. From geometric knowledge about DC motor design is observed that the width of the cooler’s cross section is equal to the width of the MEM minus width for pipebends and flanges of the cooling system.

\[ b_{cool} = D_{mot} - 2 \cdot R_{pipe} \]
Knowing the temperature difference over the air-side of the cooler (technological constant) and heat losses to the cooler during max. continuous condition, the maximum air flow is. The height of the cooler can now be calculated by the function:

\[ h_{cool} = \frac{\phi_{coolair}}{D_{cool} \cdot V_{coolair} \cdot 3600} + h_{cooladd} \]

| \( \phi_{coolair} \) | Airflow through MEM cooler | [m³/h] | Technological constant |
| \( V_{coolair} \) | Velocity through the air-side of the cooler | [m/s] | Technological constant |
| \( h_{cooladd} \) | Additional cooler height | [m] | Technological constant |

The result of this relation is only allowed when following restriction is met:

**Restriction:** The maximum cross sectional diagonal of the cooler must be smaller than the diameter of the maintenance hatch, as the cooler must periodically be removed from the submarine for maintenance reasons:

\[ \sqrt{\left( h_{cool} \right)^2 + h_{cool}^2} < D_{hatch} \text{ OR } \sqrt{\left( b_{cool} \right)^2 + h_{cool}^2} < D_{hatch} \]

| \( D_{hatch} \) | Cross-sectional diameter of hatch | [m] | Technological constant |

**MEM area calculation**
The area of the MEM is equal to its length times its width

**Assumption:** Required space for MEM is box-shaped

**MEM volume calculation**
The volume of the MEM is equal to its area times its height

**Assumption:** Required space for MEM is box-shaped

**B.4 Dynamic tests**

The purpose of dynamic evaluation is to check implemented knowledge on valid value prediction. By **validation** is meant that the computed solution is sufficiently accurate to serve the purposes for which the model was constructed. The validity of the model can be tested in several ways. First, the solutions are tested for obvious physical or mathematical constraints, such as maximum or minimum values and expected in- or decreasing behaviour. Next the computed results are compared with available data, which are obtained in the same settings as used in the mathematical model. Many times however the settings are unknown or can not be accurately measured. A typical example is the distribution of the air gap flux along the pole shoe. This distribution is simplified to an uniform distribution using a ratio.
(α) between the “active copper area" of pole (having the uniform air gap flux distribution) and total pole area (having the unknown air flux distribution). In such cases only the experience and intuition of the designer is available for judging the validity of the model. By variation of the unknown parameter value the effect on the outcome of the model can be investigated. Figure B.4 shows the (limited) effect of this ratio on the rotor diameter and rotor plus stator (motor) diameter of the Main Electric Motor.

Note - A high value for the active copper area of the pole decreases the required length of the pole pitch and thus the required rotor diameter. However, the magnetic field created by the armature increases as the contour enclosed by the armature current increases (Maxwell’s principle). As the magnetic field along the peripheral of the pole pitch must be larger than zero, the field created by the field windings must be larger than the field created by the armature. As the air gap induction is limited, the airgap thickness must increase to fulfill Maxwell’s principle for the contour enclosed by two poles. The stator yoke height increases for the same reason as the stator yoke induction is limited too. Increasing the magnetic field created by the windings requires a larger pole height. Due to the increasing air gap, pole height and yoke height, the motor diameter increases for increasing active copper area of the poles.

Figure B-4 Effect of ratio between the "active copper area" of pole and total pole area on diameter of main electric motor

During the development of the first released product dynamic evaluations are performed continuously as soon as new knowledge is added. Performing a complete test of the application’s knowledge is usually only possible during the early stage when the application is small. Later, when the body of knowledge grows, it becomes impossible to test answers to all possible questions. If so, the tests are limited to test cases. Documentation produced during the development is required to support the dynamic quality of the CEM. Continuously updating of the documents is required, while the knowledge-based and procedure-based applications evolve. The dynamic test documents are guided by check lists which include different aspects for each type of application.

Dynamic tests of knowledge implemented in knowledge-based tools are documented in so-called dynamic test forms. These forms contain a design task description, input values, flowchart of the reasoning process, expected- and detected output. Table B.3 contains an example of a dynamic test. In this example the knowledge in the Main Electric Motor sizing model is applied.
### Page of Knowledge Dictionary

<table>
<thead>
<tr>
<th>Knowledge base CEM9.166</th>
<th>Relation title: Diameter Rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class: 211 MEM MainElectricMotor</td>
<td>Version date: 12/6/98</td>
</tr>
<tr>
<td>Knowledge engineer ID: CN</td>
<td></td>
</tr>
</tbody>
</table>

**Relation code format**

\[ D_{rotor} = \frac{3^{\frac{1}{3}} \cdot PbMEM_{cont} \cdot 8.6005E-7 \cdot NoP}{N_{rev,cont} \cdot ZaMEM \cdot \eta_{MEM,Dim} \cdot K_{cu,A} \cdot B_{cont}} \]

**Relation graphical format**

\[ \text{D}_{\text{rotor}} = \frac{3^{\frac{1}{3}} \cdot \text{PbMEM}_{\text{cont}} \cdot 8.6005E-7 \cdot \text{NoP}}{\text{N}_{\text{rev,cont}} \cdot \text{ZaMEM} \cdot \eta_{\text{MEM,Dim}} \cdot \text{K}_{\text{cu,A}} \cdot \text{B}_{\text{cont}}} \]

**Relation control string**

HARD: relation is always accepted
OW: relation can only determine the rotor diameter
AND: all its constraints must be valid
PHYSICAL: relation is based on physical observations

**Relation comment**

[Diameter of rotor]

assumptions: Height armature slot: 45 [mm]
Armature current density: 5E6 [A/m²]
Ratio copper area of pole and total pole area: 2/3 [-]
Ref: K. Delerock: "Bepaling van de groote en massa van een hoofddelecromotor van een onderzeemoor", in Dutch, TU-Delft, OIMO 93/08; July 1993.

**Constraint code format**

<table>
<thead>
<tr>
<th>Constraint graphical</th>
<th>Constraint control string</th>
<th>Constraint comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ V_{rotor} &lt; 25 ]</td>
<td>HARD</td>
<td>Circumferential speed of the rotor tip must be below 25 [m/s]</td>
</tr>
<tr>
<td>TR</td>
<td>Constraint must be TRUE</td>
<td></td>
</tr>
<tr>
<td>MESSAGE</td>
<td>If not valid, return message to user</td>
<td></td>
</tr>
</tbody>
</table>

**Constraint control string**

EPS: 0.00001 Accuracy of \( \approx \) sign is \( +/- 0.00001 \) [T]

HARD: Constraint always valid
TR: Constraint must be TRUE
MESSAGE: If not valid, return message to user

**Constraint comment**

Airgap induction exceeds maximum allowable value
Advice: Increase \( \text{P MEM,cont} \), Decrease \( \text{P MEM,Burst} \)

<table>
<thead>
<tr>
<th>Name</th>
<th>Class</th>
<th>Reference</th>
<th>Default</th>
<th>unit</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>D rotor</td>
<td>211</td>
<td>Diameter Rotor</td>
<td>3</td>
<td>m</td>
<td>system</td>
</tr>
<tr>
<td>PbMEMCont</td>
<td>211</td>
<td>Power Brake MEM max. CONTinuous</td>
<td>1000</td>
<td>kW</td>
<td>system</td>
</tr>
<tr>
<td>ZaMem</td>
<td>211</td>
<td>number of (ZA) Armatures MEM</td>
<td>2</td>
<td>-</td>
<td>user</td>
</tr>
<tr>
<td>NrevCont</td>
<td>230</td>
<td>No REVolutions max. CONTinuous</td>
<td>2.5</td>
<td>1/s</td>
<td>system</td>
</tr>
<tr>
<td>NoP</td>
<td>211</td>
<td>Number of pole Pairs</td>
<td>6</td>
<td>-</td>
<td>user/sysyte</td>
</tr>
<tr>
<td>EffMEMDim</td>
<td>211</td>
<td>EFFiciency MEM for DIMensioning</td>
<td>Max: 1 0.94</td>
<td>-</td>
<td>m</td>
</tr>
<tr>
<td>KcuA</td>
<td>211</td>
<td>armature winding factor</td>
<td>0.4</td>
<td>-</td>
<td>system</td>
</tr>
<tr>
<td>B/Cont</td>
<td>211</td>
<td>air gap induction</td>
<td>0.75</td>
<td>T</td>
<td>system</td>
</tr>
</tbody>
</table>

193
### Table B.3  Dynamic test form as used in knowledge dictionary

<table>
<thead>
<tr>
<th>Knowledge base: CEM9_387.RPF</th>
<th>Description of MACRO: MEM diameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Version date:</strong></td>
<td>-Q-U-A-E-S-T-O-R-/Rev. 96.1</td>
</tr>
<tr>
<td><strong>Knowledge engineer ID:</strong></td>
<td>CN</td>
</tr>
<tr>
<td><strong>Problem discussion:</strong></td>
<td>Calc. diameter rotor and stator (motor) of MEM</td>
</tr>
<tr>
<td><strong>Requested Value(s):</strong></td>
<td></td>
</tr>
<tr>
<td>Dotor</td>
<td>Diameter of ROTOR: [m]: ?</td>
</tr>
<tr>
<td>Dmotor</td>
<td>Diameter of MOTOR: [m]: ?</td>
</tr>
</tbody>
</table>

#### Test completeness

**Discrete Input from Operator**

<p>| B0Cont | airgap induction (B0) in CONTinuous condition: [T]: | .75 |
| B0Max | airgap induction (B0) MAXimum allowalbe: [T]: | 1.08 |
| CoolType | COOLing system TYPE MEM: | 1 |
| CpCu | specific heat (CP) of copper: [J/kgK]: | 390 |
| ExisMem | EXIsiting Main Electric Motors: | -1 |
| I0 | maximum (I0) current mem armature: [A]: | 3200 |
| IhshuntMa | current (I) through shunt windings MAXimum: [A]: | 80 |
| Ja | Armature current density at max. cont. cond: [A/m²]: | 586 |
| JshtunCe | current density (J) of serie windings CORRect: [-]: | 0.91 |
| JshtunCo | current density (J) SHUNT windings CORRection: [-]: | 0.66 |
| Jw | Winding current density at max. cont. cond: [A/m²]: | 386 |
| KgCu | Armature winding space factor: [-]: | .4 |
| Mth/NCu | ratio between Mass Thermal and Mass copper: [-]: | 1.35 |
| NRevBurs | Number of REVolutions for BURST speed: [rpm]: | 200 |
| PkMem | max output Power (Brake) of MEM for a short: [kW]: | 4100 |
| PkMemCon | output Power (Brake) of MEM in maximum CONT: [kW]: | 2100 |
| ToolMem | minimum Temperature (COLD) in armature winding: [K]: | 300 |
| TCoolWet | inlet Temperature of COOLing water MEM: [K]: | 296 |
| ThotMem | maximum Temperature (HOT) in armature winding: [K]: | 403 |
| Uc | terminal (U) voltage of commutator: [V]: | 13.85 |
| UmaxMem | max. (expected voltage (U) at terminals: [V]: | 785 |
| Z6Mem | number (2) of MEM Armatures: [-]: | 2 |
| Zbldes | number (2) of propeller BLADES: [-]: | 5 |
| ZwSerie | number (2) of SERIE windings one armature: [-]: | 2 |
| Zwshunt | number (2) of SHUNT windings one armature: [-]: | 86 |
| Y | Pole area ratio (y) of MEM: [-]: | 0.66667 |
| nPi | pi (n): [-]: 3.14159265 |
| bTimeCon | bTIME warming up from COLD temp in CONT. cond. [min]: | 100 |</p>
<table>
<thead>
<tr>
<th>Description</th>
<th>Derived</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dc Diameter Commutator</td>
<td>1.30</td>
<td>1.30</td>
</tr>
<tr>
<td>DoDiameter Diameter of MOTOR</td>
<td>2.55</td>
<td>2.54</td>
</tr>
<tr>
<td>Dotor Diameter of ROTOR</td>
<td>1.94</td>
<td>1.90</td>
</tr>
<tr>
<td>EffMemBu total Efficiency of MEM in BURST cond.</td>
<td>0.932</td>
<td>0.91</td>
</tr>
<tr>
<td>EffMemCo total Efficiency of MEM in Continuous cond.</td>
<td>0.905</td>
<td>0.91</td>
</tr>
<tr>
<td>EffMemDi Efficiency MEM in max cont. cond. for design</td>
<td>0.929</td>
<td>0.91</td>
</tr>
<tr>
<td>Hpole Height of POLE</td>
<td>0.18</td>
<td>0.17</td>
</tr>
<tr>
<td>HstatorY Height of Stator Yoke</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>ImemCont max current (I) MEM of one armature</td>
<td>2412</td>
<td></td>
</tr>
<tr>
<td>IshuntCo current (I) through SHUNT one armature at max</td>
<td>32.44</td>
<td></td>
</tr>
<tr>
<td>IWexcitC ampere (I) turns (W) excitation windings one</td>
<td>7.61e+03</td>
<td></td>
</tr>
<tr>
<td>MarmCu copper Mass of one ARMature (CU)</td>
<td>545.07</td>
<td></td>
</tr>
<tr>
<td>McolCu copper Mass of COLLeector (CU)</td>
<td>745.65</td>
<td></td>
</tr>
<tr>
<td>NoP Number Of Pole pairs</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>PlossBrB Power LOSS BRushes one armature mem during BU</td>
<td>2067</td>
<td></td>
</tr>
<tr>
<td>PlossExc Power LOSS for Excitation one Armature at maxi</td>
<td>16022</td>
<td></td>
</tr>
<tr>
<td>PlossFeB Power loss MEM due to pulsation losses in iro</td>
<td>13114</td>
<td></td>
</tr>
<tr>
<td>PlossHFB Power LOSS inter- (H) Poles of one armature d</td>
<td>19584</td>
<td></td>
</tr>
<tr>
<td>PlossMem Power LOSS MEM at BURST condition</td>
<td>229.65</td>
<td></td>
</tr>
<tr>
<td>PlossMem Power Loss of MEM in max continuous cond.</td>
<td>161.69</td>
<td></td>
</tr>
<tr>
<td>PlossPsB Power LOSS Pole Shoe of one armature mem</td>
<td>8261</td>
<td></td>
</tr>
<tr>
<td>PmemAuxB Power of MEM AUXillaries in BURST condition</td>
<td>68.62</td>
<td></td>
</tr>
<tr>
<td>PmemAuxC Power of MEM AUXillaries in Continuous cond.</td>
<td>58.21</td>
<td></td>
</tr>
<tr>
<td>RserieEx Resistance SERIES excitation windings one arma</td>
<td>1.71e-03</td>
<td></td>
</tr>
<tr>
<td>RshuntEx Resistance SHUNT excitation windings one arma</td>
<td>0.97</td>
<td>1.0</td>
</tr>
<tr>
<td>ThauThr [THAU] THERmal time constant of MEM cooling</td>
<td>1664.1</td>
<td></td>
</tr>
<tr>
<td>TmemBura average Temperature of MEM windings at Burst</td>
<td>342.3</td>
<td></td>
</tr>
<tr>
<td>TmemCont average Temperature of MEM windings at max.</td>
<td>400.2</td>
<td></td>
</tr>
<tr>
<td>Votor circumferential Velocity of ROTOR</td>
<td>20.3</td>
<td></td>
</tr>
<tr>
<td>D airgap thickness between stator and rotor</td>
<td>1.3e-02</td>
<td></td>
</tr>
<tr>
<td>ØStimeCol STIME warm-up cool-water to Cold temp in CONT</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>ØStimeCol STIME warm-up cool-water to Cold temp in BURST</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>ØStimeHot STIME warm-up cool-water to Hot temp in BURST</td>
<td>1922</td>
<td>1830</td>
</tr>
</tbody>
</table>

Note: blank expected values are unknown.
PlossArmBurst:=f(PlossArmCont,10,TmemCont,TmemBurst,TmemCont)
PlossArmBurst inferred

@TimeColdBurst inferred
ThauThermMem is SUBGOAL of TmemBurst, PmemAuxBurst, EffMemBurst, Dotor, Dmator and chains to:
ThauThermMem=f(McolCu, MarmCu, Mth|MCu, Cpu, KAarmMem)
MarmCu is SUBGOAL of ThauThermMem, TmemBurst, PmemAuxBurst, EffMemBurst, Dotor, Dmator and chains to:
MarmCu=f(KCuA, Dotor, NOP)
MarmCu inferred
McolCu is SUBGOAL of ThauThermMem, TmemBurst, PmemAuxBurst, EffMemBurst, Dotor, Dmator and chains to:
McolCu=f(10, NOP, DC, Dotor)
McolCu inferred

@TimeHotBurst inferred
ThauThermMem inferred
RserieMem is SUBGOAL of PmemAuxBurst, EffMemBurst, Dotor, Dmator and chains to:
RserieMem=f(Dotor, NOP, TmemCont, Jm, JserieCorr, ZWserie)
RserieMem inferred

PmemAuxBurst inferred
PlossMemBurst is SUBGOAL of EffMemBurst, Dotor, Dmator and chains to:
PlossMemBurst=f(ZaMem, PlossArmBurst, PlossHPBurst, 10, PlossBrBurst, PlossPsBurst, PlossFeBurst, PmemBurst, NrevBurst)
PlossPsBurst is SUBGOAL of PlossMemBurst, EffMemBurst, Dotor, Dmator and chains to:
PlossPsBurst=f(Dotor, NOP, NrevBurst, NoSlots, B5Cont)
PlossPsBurst inferred

PlossFeBurst inferred
PlossFeBurst is SUBGOAL of PlossMemBurst, EffMemBurst, Dotor, Dmator and chains to:
PlossFeBurst=f(Nop, NrevBurst, B5Cont, Dotor, n, a)
PlossFeBurst inferred

PlossBrBurst inferred
PlossBrBurst is SUBGOAL of PlossMemBurst, EffMemBurst, Dotor, Dmator and chains to:
PlossBrBurst=f(ImemCont, DC, NrevBurst)
PlossBrBurst inferred

PlossHPBurst inferred
PlossHPBurst is SUBGOAL of PlossMemBurst, EffMemBurst, Dotor, Dmator and chains to:
PlossHPBurst=f(KcuA, Dotor, NOP, NoSlots, Jw, Ja, I0, ImemCont, TmemBurst)
PlossHPBurst inferred

EffMemBurst inferred
ImemCont is SUBGOAL of Dotor, Dmator and chains to:
ImemCont=f(Ja, KcuA, Dotor, NOP, NCbar)
ImemCont inferred

EffMemCont is SUBGOAL of Dotor, Dmator and chains to:
EffMemCont=f(PlossMemCont, PmemAuxCont, PmemCont)
PmemAuxCont is SUBGOAL of EffMemCont, Dotor, Dmator and chains to:
PmemAuxCont=f(ZaMem, PlossExcCont, MaxMem)
PlossExcCont is SUBGOAL of PmemAuxCont, EffMemCont, Dotor, Dmator and chains to:
PlossExcCont=f(IbshuntMem, IshuntCont, PserieMem, ImemCont, TmemCont)
IshuntCont is SUBGOAL of PlossExcCont, PmemAuxCont, EffMemCont, Dotor, Dmator and chains to:
IshuntCont=f(IwexcitCont, ImemCont, ZWserie, ZWshunt)
IwexcitCont is SUBGOAL of IshuntCont, PlossExcCont, PmemAuxCont, EffMemCont, Dotor, Dmator and chains to:
IwexcitCont=f(B5Cont, 5, n)
PlossExcCont inferred
PlossMemCont inferred
PlossMemCont is SUBGOAL of EffMemCont, Drotor, Dmotor and chains to:
PlossMemCont=f(ZaMem, PlossArmCont, XcuA, Drotor, NOP, NoSlots, Jw, Ja, TmemCont,
ImemCont, Dc, NrevCont, B3Cont, u, \omega, PbMemBurst, NrevBurst)
PlossMemCont inferred
EffMemCont inferred
Vrotor is SUBGOAL of Drotor, Dmotor and chains to:
Vrotor=f(Drotor, u, NrevBurst)
Vrotor inferred
EffMemDim inferred
EffMemDim is SUBGOAL of Drotor, Dmotor and chains to:
EffMemDim=f(PlossMemCont, PbMemCont)
EffMemDim inferred
NrevCont inferred
NrevCont is SUBGOAL of Drotor, Dmotor and chains to:
NrevCont=f(PbMemCont, PbMemBurst, NrevBurst)
NrevCont inferred
Drotor inferred
Dmotor inferred
END OF INFERENCE
APPENDIX C  PROPULSION AND ENERGY SUPPLY PERFORMANCE MODEL

This appendix presents a model for predicting the propulsion and energy supply performance model. The quality control of the development process requires evaluation of the ‘additional value’ of the propulsion and energy supply model for SUBCEM, according to Appendix B.

Adding functionality
The functionality of the system improves:

• Propulsion and energy supply are vital functions for the submarine.

Adding reliability
The reliability of the system improves:

• The propulsion and energy performance are necessary for the overall performance of the submarine. Reliable prediction of this performance contributes to the reliability of the overall performance prediction of the boat.

Adding usability
The usability of the system improves:

• The Propeller, Shafting, MEM and Batteries are specially designed or modified for each type of submarines. The prediction of propulsion and energy supply performance in off-design conditions must take into account the design characteristics of these components.

As the propulsion and energy supply performance model adds ‘value’ to the SUBCEM, a knowledge elicitation process is started by Pel [1995a] and refined by [vd Nat, 1996d] to obtain a numerical model. The results of this elicitation are compactly described in the following paragraphs.

C.1 Propulsion and energy supply

The purpose of propulsion and energy supply systems is to store, transform and transport the required amount of energy efficiently from chemical energy stored in the fuel-oil to effective propulsion power.

Two design conditions are defined for the propulsion and energy supply systems: a submerged and a snorking condition. The submerged condition defines the boat at a depth at which the effect of waves on the boat can be ignored. The snorking condition defines the boat at snorking depth, at which masts and/or periscopes can be raised.
C.2 The components of the propulsion and energy supply system

For a conventional diesel-electric submarine, the performance of the propulsion and energy supply system is evaluated by the time necessary to deliver a required amount of DC-power. The DC-energy can either be used for propulsion to fulfill the propulsion function or for hotel consumption to fulfill the energy supply function. The DC-energy is generated by converting fuel to DC-energy. Conversion can be performed by generators during snorting condition, or by Air Independent Generating systems during submerged condition. The DC-energy is transported by cables to the Main Switchboard and further to either the batteries, the hotel consumers of the Main Electric Motor. The power at the Main Switchboard must always be balanced. A surplus of power is used to charge the batteries and a shortage is overcome by discharging the batteries.

![Diagram of propulsion plant concept](image)

Figure C.1 Propulsion plant concept

C.3 The propulsion and energy supply performance model

The time required for delivering an amount of DC-power is expressed by performance parameters like:

- **Snorting rate:** the ratio between charge time and discharge plus charge time
- **Speed of advance:** average speed during a period of charging and discharging
- **Endurance:** uninterrupted operating time
- **Range:** uninterrupted operating distance

These parameters can be calculated for two different discharge conditions: a shallow discharge and a deep discharge [vd Nat., 1996d]. Shallow discharge is defined by a discharge range smaller than 10% of the capacity of the battery at 100 [h] discharge. Deep discharge is defined by a range greater than 10%. Frequently deep discharging and changing is not part of a submarine’s operational profile. Using this observation, for deep discharge only submerged endurance and range have to be determined.

To calculate the performance parameter values, the following energy transforming and transporting system are examined: Main Electric Motor plus shafting and propulsor, Batteries, and Cables plus Main Switchboard. Generators, Hoteload and Air Independent Propulsion systems are not discussed in this appendix.
**Propulsor performance calculation**

The Performance of the Main Electric Motor, shafting and propulsor is expressed by the (energy) efficiency of these systems when delivering the required amount of energy to move the boat at a required speed. This effective propulsion power is equal to the resistance of the boat times its speed. For submarines the propulsion power prediction is described in detail by Holtackers [1992].

The propulsion efficiency ($\eta_d$) is the ratio between effective propulsion power and the mechanical power to rotate the propeller. This efficiency can be divided into parts which are related to the propulsor without hull and to a part which includes the hull-propulsor interaction:

$$\eta_d = \eta_h \eta_0 \eta_r$$

Efficiency of propulsor:

$\eta_0$ open water eff. from open water prop. diagram [-]

The open water efficiency is dependent on type, size, rotation rate of propulsor. A typical submarine propulsor is a multi-bladed propeller. The efficiency can be estimated using the Wageningen B-Series [Oosterfeld, 1975].

Effect of the hull on the performance of the propulsor (compared to open water condition):

$\eta_h$ hull eff., reflects diff. in thrust and mean inflow [-]
$\eta_r$ relative rotative efficiency, reflects diff. in torque [-] Technological constant

The hull efficiency is calculated by:

$$\eta_h = \frac{1-t}{1-w}$$

$t$ thrust deduction factor [-]
$w$ wake fraction [-]

The thrust deduction factor and wake fraction be calculated using the approximation given by [Holtackers, 1992].
\[ w = w_1 + w_2 \]
\[ w_1 = \text{RudderFactor} + 0.919 \cdot \frac{C_p}{\left( \frac{L_{oa}}{B_{oa}} \right)} \]
\[ w_2 = \text{IF } \frac{D_{\text{prop}}}{B_{oa}} < 0.7 \text{ THEN } 1.065 \left( 0.7 - \frac{D_{\text{prop}}}{B_{oa}} \right) - 0.038 (1-w_1) \text{ ELSE } 0 \]
\[ t = 0.41 \text{ w} \]

- **RudderFactor**: const. value depending on rudder type
- **C_p**: prismatic coefficient of hull
- **L_{oa}**: length overall of hull
- **B_{oa}**: width overall of hull
- **D_{prop}**: diameter of propeller

This approximation can be improved by including the effect of forward speed [Nat, 1996d].

**Shafting performance calculation**

The shaft efficiency is the ratio between the mechanical power at the propeller and the mechanical power to rotate the shaft. The shaft losses are divided into bearing losses and thrust block losses.

**Bearing losses**

The shafting system of a submarine is assumed to have two bearings, one oil-lubricated and one water-lubricated bearing. The power loss due to friction is calculated by:

\[ P_{\text{loss, bearing}} = \mu_{\text{bearing}} N_{\text{shaft}} D_{\text{shaft}} \pi n_{\text{rev}} \]

- **P_{\text{loss, bearing}}**: power loss of bearing
- **\mu_{\text{bearing}}**: friction coefficient bearing
- **N_{\text{shaft}}**: normal force of shaft on bearing
- **D_{\text{shaft}}**: diameter shaft
- **n_{\text{rev}}**: number of revolutions shaft submerged

In which the friction coefficient is dependent on the number of revolutions:

\[ \mu_{\text{bearing}} = a_{\text{bearing}} \frac{n_{\text{rev}}}{n_{\text{rev,Burst}}} + b_{\text{bearing}} \frac{n_{\text{rev}}}{n_{\text{rev,Burst}}} \]

- **a_{\text{bearing}}**: shaft bearing match coefficient
- **b_{\text{bearing}}**: shaft bearing match coefficient

From the results of experimental studies [Pollock, 1985], the technological constants in the
model are determined [Wilgenhof, 1996].

**Thrustblock losses**
The type of thrustblock is assumed to be axial. The power loss due to friction is predicted as a fraction of the (maximum) power loss for a deep divided boat at burst speed:

\[
P_{\text{loss, thrust}} = P_{\text{loss Max, thrust}} \left( \frac{n_{\text{rev}}}{n_{\text{rev,Burst}}} \right)^{a_{\text{thrust}}} \left( \frac{T}{T_{\text{max}}} \right)^{b_{\text{thrust}}}
\]

- \( P_{\text{loss, thrust}} \): power loss of Thrustblock [kW]
- \( P_{\text{loss Max, thrust}} \): maximum power loss of Thrustblock [kW]
- \( T \): thrust due to propulsion and seawater pressure [kN]
- \( T_{\text{max}} \): Max thrust due to propulsion & seawater pressure [kN]
- \( a_{\text{thrust}} \): Thrustblock matching coefficient [-]
- \( b_{\text{thrust}} \): Thrustblock matching coefficient [-] Technological constant

The maximum thrust acts on the thrustblock when the boat moves at maximum diving depth and at maximum speed (however, for safety reasons this condition must be avoided). The maximum power loss in this condition for the thrust block is assumed to be a fraction of the propulsion power at the shaft in burst condition:

\[
P_{\text{loss Max, thrust}} = C_{\text{thrust}} \cdot P_{\text{shaft,Burst}}
\]

- \( P_{\text{shaft,Burst}} \): power for propulsion at burst speed [kW]
- \( C_{\text{thrust}} \): Thrustblock matching coefficient [-] Technological constant

**Main Electric Motor performance calculation**
The Main Electric Motor efficiency is the ratio between the mechanical power at the shaft and the DC-power at the terminals of the MEM. Two models have been developed for predicting the MEM efficiency: a model based on curve fitting [Pel, 1995a] and a model based on Joule heat losses in armature and interpoles, ohmic and frictional brush losses, excitation losses, bearing friction losses, iron losses and pole shoe pulsation losses [vd Nat, 1996d]. The first model describes a polynom between the MEM power and the MEM efficiency of existing MEM designs. The second model is based on first principles, permitting predicting the MEM efficiency of non-existing MEM designs. The model is based on a detailed model for calculating the MEM efficiency at the 'maximum continuous' design condition Pel [1995a]. With some modifications this model can predict the efficiency at off-design conditions. The model includes the following models:

**Joulean losses**
The Joulean heat losses are caused by the current through the armature and through the interpoles. Note that the losses caused by current through the poles are part of the excitation losses. The armature Joulean heat losses \( P_{v,a} \) are calculated by:

\[
P_{v,a} = Z_a \cdot R_a \cdot \sum I_a^2 \cdot \left( \frac{I_{\text{mem}}}{I_{\text{mem,Cont}}} \right)^2
\]

with armature winding resistance \( R_a \):

203
\[ R_a = \rho \cdot \frac{(2 \cdot I_e + k_{1s} \cdot I_e)}{A_{Cu,a}} \]

and sum of armature currents in maximum continuous condition:

\[ I_{mem_{cont}} = \sum I_a = J_a \cdot A_{Cu,a} \]

**Imem** current through one armature [A] INPUT

**Imem_{cont}** current through one armature at design condition [A]

**\( \rho \)** specific resistance of copper [\( \Omega \cdot m \)] MEM sizing model

**\( l_s \)** length of winding head [m]

**\( l_o \)** length of armature conductor (iron length) [m]

**\( k_u \)** air factor of rotor yoke [m]

**\( A_{Cu,a} \)** cross-sect. copper area of the armature windings [m²]

The current through one armature is calculated by:

\[ I_{mem} = \frac{P_{mem}}{1000} \cdot \frac{1}{U_{mem}} \cdot Z_{aMem} \]

**P_{mem}** output power one armature [kW] INPUT

**U_{mem}** voltage at terminals one armature [V]

**Restriction:** This current must be smaller than the maximum allowable current (\( I_o \)).

The voltage at the terminals of the MEM is determined by the voltage at the terminals of the armature chopper and the chopper ratio:

\[ U_{mem} = U \cdot U_{chopper} \cdot U_{chopper} \]

**U_{chopper}** voltage at terminals one armature chopper [V] Cable Perf. Model

**U_{chopper}** armature voltage chopper ratio [–] INPUT

**Restriction:** This voltage must be smaller than the maximum allowable voltage (\( U_o \)), which determines the number of commutating bars.

The interpole Joulean heat losses (\( P_{v, hp} \)) are calculated by:

\[ P_{v, hp} = Z_s \cdot R_{hp} \cdot \sum I_{hp}^2 = Z_s \cdot R_{hp} \cdot \frac{\sum I_a^2}{(2 \cdot p)^2} \cdot \left( \frac{I_{mem}}{I_{mem_{cont}}} \right)^2 \]

\[ R_{hp} = 2p \cdot \rho \cdot \frac{2l_{hp} + 2b_{hp}}{A_{Cu,hp}} \]

**\( l_{hp} \)** length of interpole [m] MEM sizing model

**\( b_{hp} \)** length of winding head interpole [m] MEM sizing model

**\( A_{Cu, hp} \)** cross-sect. copper area of the interpole windings [m²] MEM sizing model
**Ohmic brush losses**
The voltage drop at the brush is assumed to have a technological constant value, thus the ohmic brush losses \( P_{\nu,b} \) are linear dependent on the armature current.

\[
P_{\nu,b} = Z_a \cdot \Delta u \cdot I_{\text{mem}}
\]

\( \Delta u \) voltage drop at brush of commutator [V] Technological constant

**Frictional losses**
The friction coefficient is assumed to have a technological constant value, thus the frictional losses of the bearings and the brushes are linear dependent on the rotation speed of the armatures \( v_{\text{shaft}} \).

Frictional losses \( P_{\nu,1} \) of the two bearings:

\[
P_{\nu,1} = 2 \cdot F_w \cdot v_{\text{shaft}}
\]

\[
= 2 \left( n_{\text{c}} \cdot 2 \pi n_{\text{rev}} \cdot \left( \frac{D_{b,\text{shaft}}}{\epsilon} \right)^2 \cdot 2 \pi l_b \right) \cdot \left( 2 \pi n_{\text{rev}} \cdot \frac{D_{b,\text{shaft}}}{2} \right)
\]

\( n_{\text{c}} \) dynamic viscosity of lubricating oil [Ns/m²] Technological constant
\( \epsilon \) bearing clearance [m] Technological constant
\( D_{b,\text{shaft}} \) diameter of bearing [m] MEM sizing model
\( l_b \) length of bearing [m] MEM sizing model

Frictional losses \( P_{\nu,b} \) of brushes:

\[
P_{\nu,b} = Z_a \cdot \sum A_b \cdot F \mu_b \cdot d_k \pi n_{\text{rev}}
\]

\( d_k \) diameter of the commutator [m] MEM sizing model
\( A_b \) contact area of the brushes-commutator [m] MEM sizing model
\( \mu_b \) brush friction coefficient [-] Technological constant
\( F \) brush pressure [N/m²] Technological constant

**Excitation losses**
The excitation losses \( P_{\nu,\ell} \) consists of Joulean losses of series and shunt windings:

\[
P_{\nu,\ell} = R_{\text{serie Mem}} I_{\text{mem}}^2 + R_{\text{shunt Mem}} \cdot I_{\text{shunt}}^2
\]

\( R_{\text{serie Mem}} \) resistance series windings one armature [Ω]
\( R_{\text{shunt Mem}} \) resistance shunt windings one armature [Ω]
\( I_{\text{shunt}} \) current through shunt windings [A]

To calculate the current through the shunt windings, first the number of ampere turns is calculated from the electro motive force by applying the 2\(^{nd}\) law of Maxwell:

\[
\text{Emf} = \left( \frac{\mu_b}{\delta} \right) \alpha \tau_p \cdot D_{\text{rotor}} \pi n_{\text{rev}} \cdot \text{NoSlots}
\]
Within this relation the Electro Magnetic force is calculated from the power balance:

\[ \text{Emf} = \text{Umem} - (\text{Imem} R_a + \Delta u + \text{Imem} R_{np}) \]

The result of this relation is only allowed when the following restriction is met:

**Restriction:** The magnetic field along the peripheral of the pole pitch must be larger than zero. This requires that the field created by the field windings must be larger than the field created by the armature:

\[ \text{IW} \geq \frac{k_{CUL}}{2} h_n b_n \left( \frac{\text{Imem}}{\text{Imem}_{cont}} \right) \frac{J_a}{\tau_n} \tau_p \alpha \]

- \( k_{CUL} \): armature winding space factor
- \( h_n, b_n \): slot area
- \( \tau_n \): peripheral length of the slot pitch
- \( J_a \): armature current density at design condition

If this restriction is not met, then the value \( U/U_{\text{chopper}} \) should be deceased below 1. Note that the armature current must be lower than maximum allowable current through the chopper.

The shunt field current can now be calculated from:

\[ \text{IW} = ZwSerie \text{Imem} + ZwShunt \text{Ishunt} \]

- \( ZwSerie \): number of series windings
- \( ZwShunt \): number of shunt windings

**Restriction:** The field windings must be able to generate the number of ampere windings:

\[ \text{Ishunt} \leq \text{IshuntMax} \]

- \( \text{IshuntMax} \): maximum current through shunt windings

The resistance of the windings can be calculated using the assumption:

**Assumption:** The winding contour for both series and shunt windings are equal
\[ R_{\text{seriemem}} = \frac{P_{\text{lossexcitcont}} - R_{\text{shunt}} I_{\text{shunt}}^2}{I_{\text{mem}}^2} \]
\[ R_{\text{shuntmem}} = \frac{R_{\text{seriemem}} Z_{\text{shunt}} I_{\text{mem}} I_{\text{cont}} J_\Omega}{Z_{\text{srie}} I_{\text{shuntmax}} J_\alpha} \]

\[ J_\omega \quad \text{winding current density at design condition} \quad [\text{A/m}^2] \quad \text{Technological constant} \]

The resistance of the exciting winding for maximum continuous condition \((P_{\text{lossexcitcont}})\) can be found from:
\[ P_{\text{lossexcitcont}} = Z_a \cdot I_{\text{mem}}^2 \cdot 2 \cdot p \cdot R_\varepsilon \]

The resistance of one exciting winding can be found from:
\[ R_\varepsilon = \rho \cdot \frac{O_w}{A_{\text{Cu,p}}} \]

\[ A_{\text{Cu,p}} \quad \text{cross sectional copper diameter of exciting winding} \quad [\text{m}^2] \quad \text{MEM sizing model} \]
\[ O_w \quad \text{contour of the exciting winding} \quad [\text{m}] \quad \text{MEM sizing model} \]

**Iron and pole shoe pulsation losses**

The iron and pole pulsation losses are linear dependent on the rotation speed of the armature(s).

The iron losses \((P_{v,\text{Fe}})\) are calculated using a so-called loss-number:
\[ P_{v,\text{Fe}} = Z_a \cdot V_e \cdot V_{s_j} \]

\[ V_a \quad \text{iron volume of the armature} \quad [\text{m}^3] \quad \text{MEM sizing model} \]

Deleroi [1993a] gives an empirical relation for the loss number \((v_e)\):
\[ v_e = 0.525 \cdot 10^{-5} \cdot p \cdot n_{\text{rev}} \cdot (100 + p \cdot n_{\text{rev}}) \cdot B_{\text{max}}^2 \]

\[ B_{\text{max}} \quad \text{maximum flux density in the armature iron} \quad [\text{T}] \quad \text{Technological const.} \]
**Power consumption fans**
The voltage at the terminals of the fans is equal to the voltage at the terminals of the armature. The power consumption of the fans is related to this voltage by an empirical relation. This relation is derived by applying data of an existing MEM.

**Chopper losses**
The chopper for the armature current and field current are required for dead-slow speed condition, when the electro motive force becomes smaller then the voltage of one battery. The chopper losses are assumed to have a technological constant value.

**Cable performance calculation**
The cable performance model determines the cable efficiency of the cables between on one side the switchboard and on the other side a MEM armature, generator or a battery. The calculation of the MEM cable efficiency is presented as an example.

The MEM cable efficiency is the ratio between the DC-power at the terminals of the MEM and the DC-power at the terminals of the switchboard. The power loss can be calculated using Ohm’s law. To calculate this efficiency the model requires input values for: voltage at the terminals of switchboard and input power of MEM.

\[ P_{memSb} = P_{mem} + \frac{Z_{mem}}{1000} I_{mem}^2 R_{CabSbMem} \]

- \( R_{CabSbMem} \): resistance of cables Switchboard - MEM \([\Omega]\)
- \( P_{memSb} \): power of MEM at switchboard \([kW]\)

The resistance of the cable between the switchboard and the terminals of one armature is determined by the cable sizing model. This model calculates the resistance based on a defined maximum voltage drop for the maximum allowable current through a MEM armature and almost fully discharged batteries.

The current through the cable is:

\[ I_{mem} = \frac{P_{memSb} Z_{Serie}}{1000 U_{sb} Z_{mem}} \]

- \( U_{sb} \): voltage at terminals switchboard \([V]\)  Switchboard perf.

The voltage at the terminals of the armature chopper is determined by the switch-board voltage:

\[ U_{chopper} = \frac{U_{sb}}{Z_{Serie}} - I_{mem} \frac{Z_{Serie}}{Z_{mem}} R_{CabSbMem} \]

- \( Z_{Serie} \): number of armatures in series \([-]\) INPUT

**Switchboard performance calculation**
The switchboard performance model determines the power balance between the power suppliers and consumers. By switching the number of batteries in parallel and number of
armatures in series it determines the voltage at the terminals of the switchboard and at the terminals of the armature chopper.

**Assumption:** The switchboard itself has no energy losses.

**Battery performance calculation**
The battery performance model determines the battery power loss and the voltage at the terminals of a battery.

Most battery types have an internal resistance and a voltage drop between discharge and charge, resulting in a cycle loss: more energy is necessary to charge the battery than can be retrieved while discharging. The battery power and voltage are calculated by:

\[
P_{\text{batt}} = \frac{U_{\text{batt}} I_{\text{batt}}}{1000}
\]

\[
U_{\text{batt}} = U_{\text{oc Batt}} + \text{SIGN} \cdot I_{\text{batt}} \cdot R_{\text{batt}} + \delta U
\]

**SIGN**
-1: discharge, +1: charge

**Pbatt**
Power from or to battery [kW]

**Uoc Batt**
voltage open circuit of battery [V]

**Ibatt**
current through battery [A]

**RiBatt**
real internal resistance of battery [Ω]

\[
\delta U
\]

the voltage gap between discharge and charge [V] Technological constant

**Restriction:** The cell voltage during charging is lower than the gassing voltage.

The internal resistance is equal to the voltage between open circuit cell voltage and the measured voltage, divided by the current through the cell. The voltage drop or rise can be measured for existing cells for a range of (dis-)charge conditions and currents. These measurements typically show for lead-acid batteries, see also figure 6.18:

- maximum capacity of a battery cell is dependent on the current
- open circuit voltage of a battery cell is dependent on the cell (dis-)charge state
- actual cell voltage is dependent on the current and cell (dis-) charge state
- the voltage for charge condition must rise extra due to a polarization effect from discharge to charge

The relation between state of battery relative to 100 hours discharge \((x)\) and relative to maximum discharge capacity at actual current \((y)\) is:

\[
y = \frac{x \cdot C_{100}}{C_{\text{batt}}}
\]

\[
C_{\text{batt}} \quad \text{maximum capacity for actual current} \quad [\text{Ah}]
\]

\[
C_{100} \quad \text{maximum capacity for 100 hours discharge current} \quad [\text{Ah}]
\]

The capacity at 100 hours discharge is mainly proportional to the cell’s weight. For each cell type the specific capacity [Ah/kg] is almost independent from the absolute cell size, and can thus be taken as a technological constant.
The maximum cell capacity in the battery characteristic can be described by the following function:

\[
C_{\text{batt}} = C_{100} \cdot \left( \varepsilon + (1 - \varepsilon) e^{\frac{1}{\text{BattCell.d}}} \right)
\]

Sign
-1: discharge, +1: charge

\varepsilon
ratio specific cap. at infinite disch. current and \(Q_{100} \) [-] Technological constant

d = \frac{C_{100}}{\tau}

with:
\[ \tau = 100 \ln \left( \frac{1 - \alpha}{\gamma - \alpha} \right) \]

\[ \alpha = \frac{c_0}{c_\infty}, \quad \gamma = \frac{C_{100}}{c_\infty} \]

\(c_0\)
maximum cell capacity at 0 hour discharge [Ah] Technological constant

\(c_\infty\)
maximum cell capacity at infinite hours discharge [Ah] Technological constant

The open circuit cell voltage in the battery characteristic can be described by the following function:

\[
U_{\text{ocCell}} = Z_{\text{BattCell}} U_{\text{ocCellMax}} \left( 1 - a_{\text{batt}} x^{b_{\text{batt}}} \right)
\]

\(U_{\text{ocCell}}\)
open circuit cell voltage [V] Technological constant

\(U_{\text{ocCellMax}}\)
maximum open circuit cell voltage [V] Technological constant

\(a_{\text{batt}}\)
open circuit cell voltage matching coefficient [-] Technological constant

\(b_{\text{batt}}\)
open circuit cell voltage matching coefficient [-] Technological constant

\(X\)
cell condition relative to 100 h discharge [-] INPUT

\(Z_{\text{BattCell}}\)
number of battery cells in series in a battery [-] INPUT

From practical experiences is found that the ratio between voltage drop (for a discharge current) and discharge current is only dependent on the discharge state relative to maximum capacity at actual current (\(y\)). Thus, this ratio (or so-called 'pseudo' internal resistance) is not dependent on the discharge current. To describe the 'pseudo' internal resistance (\(R_{\text{Batt pseudo}}\)) a two parameter model is used:

\[
R_{\text{Batt pseudo}} = R_{0\text{Batt pseudo}} \left( 1 + c_{\text{Batt}} y^{d_{\text{Batt}}} \right)
\]

\(c_{\text{Batt}}\)
internal resistance matching coefficient [-] Technological constant

\(d_{\text{Batt}}\)
internal resistance matching coefficient [-] Technological constant

\(R_{0\text{Batt pseudo}}\)
'pseudo' internal resistance for a full battery [m\(\Omega\)] Technological constant

From battery data is found that the 'pseudo' internal resistance for a full battery depends on
the type, size and ratio between cell height and cell volume.

Using the above given models, the cell voltage of the battery in any condition (battery state and current) can be calculated. The real internal resistance is equal to the voltage between open circuit cell voltage and the calculated voltage, divided by the current through the cell. The actual current can only be calculated by solving a cycle which contains the models to determine the actual battery capacity, and battery voltage.

For charge the above described models can be used to determine the voltage increase. However, the internal resistance during charging at a battery state 'x' relative to 100 hours discharge is assumed to be equal to the internal resistance during discharge at a battery state '1-x'.

Performance parameters calculation shallow (dis-)charge
For shallow (dis-)charge the performance the performance parameters can be calculated when the charging and discharging time are known:

\[
IR = \frac{TchShallow}{TchShallow + TdisShallow}
\]

\[
SOA = IR \cdot \frac{v_{\text{snort}} + (1-IR) \cdot v_{\text{subm}}}{1 - IR}
\]

\[
\text{Endurance} = \frac{\text{MnetFuel}}{1000 \cdot \text{SFC}_{de} \cdot P_{de} \cdot IR} \cdot \frac{1}{24}
\]

\[
\text{TotRange} = \text{SOA \cdot Endurance} \cdot \frac{3600}{1852}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR</td>
<td>indiscreration rate</td>
<td>[-]</td>
</tr>
<tr>
<td>SOA</td>
<td>speed of advance</td>
<td>[m/s]</td>
</tr>
<tr>
<td>Endurance</td>
<td>maximum uninterrupted operating mission time</td>
<td>[days]</td>
</tr>
<tr>
<td>TotRange</td>
<td>total range without refueling</td>
<td>[nm]</td>
</tr>
<tr>
<td>TchShallow</td>
<td>shallow charging time</td>
<td>[h]</td>
</tr>
<tr>
<td>TdisShallow</td>
<td>shallow discharge time</td>
<td>[h]</td>
</tr>
<tr>
<td>v_{snort}</td>
<td>snorting speed</td>
<td>[kn]</td>
</tr>
<tr>
<td>v_{subm}</td>
<td>submerged speed</td>
<td>[kn]</td>
</tr>
<tr>
<td>MnetFuel</td>
<td>net fuel mass</td>
<td>[t]</td>
</tr>
<tr>
<td>Pde</td>
<td>power running diesel engines</td>
<td>[kW]</td>
</tr>
<tr>
<td>SFCde</td>
<td>Specific fuel consumption diesel engines</td>
<td>[g/kWh]</td>
</tr>
<tr>
<td></td>
<td>Diesel engine sizing model</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diesel engine perf model</td>
<td></td>
</tr>
</tbody>
</table>

The charging and discharging time are calculated by dividing the battery capacity times the shallow discharge range by respectively the charge current and discharge current. Both currents are determined at the mean value of the battery (dis-)charge range.
\[ T_{\text{disShallow}} = \int_{x_{\text{min}}}^{x_{\text{max}}} \frac{C_{100}}{I_{\text{batt\_dis}(x)}} \, dx = \frac{C_{100} \cdot (x_{\text{max}} - x_{\text{min}})}{I_{\text{batt\_dis}} \left( \frac{x_{\text{max}} + x_{\text{min}}}{2} \right)} \]

\[ T_{\text{chShallow}} = \int_{x_{\text{min}}}^{x_{\text{max}}} \frac{C_{100}}{I_{\text{batt\_ch}(x)}} \, dx = \frac{C_{100} \cdot (x_{\text{max}} - x_{\text{min}})}{I_{\text{batt\_ch}} \left( \frac{x_{\text{min}} + x_{\text{max}}}{2} \right)} \]

**Performance parameters calculation deep (dis-)charge**

For deep discharge the discharge time \( (T_{\text{disdeep}}) \) is calculated. As the battery voltage and capacity continually changes during the constant power discharge, the following integral must be calculated:

\[ T_{\text{disDeep}} = \int_{x_{\text{min}}}^{x_{\text{max}}} \frac{C_{100}}{I_{\text{batt\_dis}}(x)} \, dx \]

\[ = \int_{y_{\text{min}}}^{y_{\text{max}}} \left[ \frac{C_{\text{batt}}(y)}{I_{\text{batt\_dis}}(y)} + \frac{y}{I_{\text{batt\_dis}}(y)} \frac{dC_{\text{batt}}}{dI_{\text{batt}}} + \frac{dI_{\text{batt\_dis}}}{dy} \right] \, dy \]

\( T_{\text{disDeep}} \) operating time between two shunting periods \([\text{h}]\)

\( y \) battery condition relative to actual battery capacity \([-]\)

\( Y_{\text{max}} \) maximum discharge condition \([-]\)

\( Y_{\text{min}} \) minimum discharge condition \([-]\)

For constant power discharge the derivative of the current to the discharge condition relative to the actual battery capacity is obtained from differentiating:

\[ P_{\text{batt}} = I_{\text{batt}} U_{\text{oc\_batt}}(y) - I_{\text{batt}}^2 R_{\text{batt\_pseudo}}(y) = \text{constant} \]

Resulting in:

\[ \frac{dI_{\text{batt}}}{dy} = \frac{dU_{\text{oc\_batt}}}{dy} + I_{\text{batt}} \frac{dR_{\text{batt\_pseudo}}}{dy} - 2 I_{\text{batt}} R_{\text{batt\_pseudo}} \]

The integral to calculate the deep discharge time is solved numerically e.g. using Simpson's rule. At the end of the discharge range the step size is decreased, as the strongest non-linear behaviour of the maximum actual capacity and voltage occurs in this part of the discharge range.

For deep discharge the discharge time is calculated. As the battery voltage and capacity continually changes during the constant power discharge, the following integral must be calculated:
\[ T_{\text{disDeep}} = \int_{x_{\text{min}}}^{x_{\text{max}}} \left[ \frac{C_{100}}{I_{\text{batt}}(x)} \right] dx = \int_{y_{\text{min}}}^{y_{\text{max}}} \left[ \frac{C_{\text{batt}}(y)}{I_{\text{batt}}(y)} + \frac{y}{I_{\text{batt}}(y)} \right] \frac{dI_{\text{batt}}}{dy} dy \]

- \( T_{\text{disDeep}} \) operating time between two discharging periods [h]
- \( y \) battery condition relative to actual battery capacity [-]
- \( y_{\text{max}} \) maximum discharge condition [-]
- \( y_{\text{min}} \) minimum discharge condition [-]

### C.4 Dynamic tests

Dynamic test of propulsion and energy supply performance models is shown in graphical way by figure C.2. The figure shows the iterative calculation of the discharge time.

**Figure C.2** Propulsion and energy supply performance model represented in a flow diagram
REFERENCES

Adelman, 1992

Akagi, 1991
S. Akagi: “Expert system for Engineering Design Based on Object-Oriented knowledge Representation Concept”, in: "Artificial intelligence in design" (D.T. Pham, editor); Springer Verlag London Limited; 1991.

Allmendinger, 1990

Andre, 1986

Andrews, 1985

Andrews, 1996

Arentzen, 1960

Berkhout, 1987

Bijlaard, 1957

Burcher, 1994
Buxton, 1992

Bresse, 1866
M. Bresse: "Cours de mécanique appliquée", second edition; pag. 334; 1866.

Broughton, 1962
W.J. Broughton: "Limit design of stiffened rectangular plates under lateral loading with application to ship bulkheads", Royal Canadian Navy; SNAME meeting; May 1962.

Brown, 1987

BS5500, 1994

Carlson, 1987

Carrol, 1865

Claessen, 1994

Cort, 1987

Coyne, 1989

Christiaans, 1992

Dai, 1994

Daniëls, 1996
S.J.J. Daniëls: "Validatie van het SUBSPACE model - door middel van invoering van de machinekamer gegevens van een onderzeeboot", OEMO 96/03, TU-Delft, in Dutch; March 1996.
Deleroi, 1993a

Deleroi, 1993b

Dent, 1987

van Diermen, 1995

Durkin, 1994

Dustmann, 1992

v Duuren, 1993-1995

Dym, 1991

Eames, 1976
M.C. Eames, T.G. Drummond: “Concept Exploration - an Approach to Small Warship Design” The Royal Institute of Naval Architects; 1977.

Faulkner, 1983

Faulkner, 1991

Foley, 1994
Georgescu, 1990
C. Georgescu; F. Verbaas; H. Boonstra: “Concept Exploratie Models for merchant ships”, CFD and CAD in Ship Design; Elsevier Science Publishers B.V.

Golub, 1992

Gorman, 1991

Groen, 1996

Guida, 1993

Guida, 1994

van Hees, 1991

van Hees, 1992

van Hees, 1993

van Hees, 1995

van Hees, 1997

Heggstad, 1981

Heggstad, 1984

218
Hemond, 1985

Hills, 1989

Hinton, 1992

Hodgson, 1991

Hoerner, 1965

Holtackers, 1991

Holtackers, 1992

Holtackers, 1993a

Holtackers, 1993b

Hope, 1981

Huggins, 1994

Humphrey, 1976

Hyde, 1992
Jackson, 1983

Jackson, 1989

Jackson, 1992

Jiskoot, 1998

Kaminski, 1995

Kaminski, 1996

Kendrick, 1970

Kendrick, 1994

KM, 1991
Author unknown: “Algemene normen voor de accommodatie bij de koninklijke marine - deel 3 onderzeebooten”, Royal Netherlands Navy 1 VVKM 9.3; Ministrieel Defensie Besluit S6741/982; NATO G7610-17-051-3499; in Dutch; January 1991.

Knaack, 1991

van Kuilenburg, 1994

Lambert, 1996
Laansma, 1992

Lee, 1991

Loid, 1983

MacCallum, 1982
K.J. MacCallum: “Understanding relationships in marine systems design”, IMSDC 82; Dept. of Ship and Marine Technology - University of Strathclyde, Glasgow; April 1982

MacCallum, 1985

MacCallum, 1987

MacCallum, 1989

MacCallum, 1990

MacCallum, 1993

MacGregor, 1990

Márík, 1992
Miles, 1994

Mistree, 1991

von Mises, 1914

Nat, 1993a

Nat, 1993b

Nat, 1994

Nat, 1995

Nat, 1995

Nat, 1996a

Nat, 1996b

Nat, 1996c

Nat, 1996d

Nash, 1995
NavSea, 1985

Nethercote, 1982

Netten, 1993

Nordin, 1990

Oele, 1993

Oosterveld, 1975

Pegg, 1987

Pel, 1995a

Pel, 1995b

Prins, 1988

Prins, 1996
C.A. Prins, B. Everard: “Approaches to submarine design in a changing environment”, INEC 96, Warship design What is so different; The Institute of Marine Engineers; April 1996.

Prins, 1998
C.A. Prins: “Results of a benchmark test for the propulsion power of a 1800 ton submerged displacement submarine” privat conversation; 1998.
Pollock, 1985

Reijmers, 1986

Rentema, 1998

Sahm, 1994

Schaap, 1990
A. Schaap, T. van Terwisga: “The power of a CEM in innovative ship design” Intern. Symp. on CDF and CAD in ship design, paper 5; Sept. 1990.

Schild, 1992

Schreiber, 1992

Sekimoto, 1989

Sen, 1990

Serrano, 1992

Sipkema, 1993

Stapersma, 1992

Stapersma, 1998

224
Stenard, 1988

Sussman, 1992
G.J. Sussman “Invited talk”, AAAI Fall Symp. Series - Design from Physical Principles

Swaan Arons, 1991

Timoshenko, 1936

Tong, 1992

Townsin, 1983
R.L. Townsin: “Ship design for fuel economy, bottom condition and fuel conservation”, 8th West European Graduate Education in Marine Technology; University of Newcastle upon Tyne, August 1983.

Varta, 1991
Varta: “Rechargeable storage batteries for traction application”, Varta R&D, Teb 91/1.4; 1991.

Vucinic, 1994

Waldron, 1992

Weisberg, 1986

Welsh, 1990

Westen, 1991
Wilgenhof, 1996
J. Wilgenhof: “Bepaling van de dimensies en prestaties van mechanische transmissie en diesel motor gas huishouding van een onderzeeboot”, NEVESBU; in Dutch; 1996.

Williams, 1962
A. Williams: “Mathematical representation of bodies of revolution by use of a digital computer”, Statens Skeppspovningsanstalt, nr. 51; Scandinavian University books; Göteborg.

Wilson, 1966

de Wit, 1994

Yuan, 1991
SUMMARY

A Concept Exploration Model for Submarine Design using knowledge-based techniques

Conceptual design is the first phase in the design process in which both the design problem and the way to solve the problem are not exactly known. Starting with an initial specification, the most promising concept should be generated. However, as the design process proceeds more information becomes available, which may introduce new design questions or revise the original problem. As a result a variety of questions can be asked during the problem solving process, making a strategy based on a fixed process not useful. For this reason a knowledge-based shell QUAESTOR, developed by Maritime Research Institute Netherlands, is chosen for assisting the designer in solving complex design problems. One of the key features of such a shell is the distinction it makes between numerical knowledge, represented by the parameters, relations and constraints, and the way this knowledge is used for predicting the performance of a design.

The conceptual design stage of a submarine is complex, because the relationship between the design characteristics and its performance is not always straight forward. Changing a characteristic may improve one specific performance while worsening another. The traditional way of dealing with this complexity was to base a new concept on well-described previous designs. The performance characteristics of these concepts can be calculated using a model in which both in- and output are fixed: the so-called directed network approach. Systems using this approach for generating large numbers of concept designs are called traditional Concept Exploration Models. These traditional systems have two major limitations:

- **Limiting free creativity** - The conceptual design can be characterised by an intensive dialogue between a client and a design team. In this dialogue different types of questions arise, requiring different design descriptions and calculations. This implies that the control of the design process should be data-driven, as opposed to procedure-driven in the traditional systems. In traditional systems the design models and the application of these models are inseparable. Often, the implemented models are not even shown to the designer. This makes the updating for new design problems and/or new design knowledge difficult and expensive.

- **Design knowledge is represented in numerical format only** - All design knowledge is represented in numerical format. An internal arrangement can only be modelled by numerical knowledge, making it difficult to change the geometrical and topological knowledge of a concept.
To overcome these drawbacks an un-directed network approach is used, which includes design knowledge in numerical, geometrical and topological format. This thesis describes the major issues which have risen during the development of a conceptual design tool based on this approach. Each step in the development process has been examined: identifying the problem, learning about the design-knowledge and its structure, selecting knowledge sources and extracting the knowledge from them, selecting the most promising supporting tools, encoding the knowledge in the tool, verifying, validating and applying the encoded knowledge. The development process guiding to a conceptual design tool is demonstrated for conceptual design of submarines with a submerged displacement between 1000 - 3000 [ton]. The study resulted in a large amount of knowledge on various design aspects of submarines.

The developed prototype, called SUBCEM, shows the feasibility of the tool for predicting the size and performances of submarines in the conceptual stage of the design process. The designer can concentrate on the overall design process, while leaving details to the specialist who has implemented the knowledge. Design alternatives caused by different components and/or layouts can be investigated more robustly as the concept exploration model is capable of integrating numerical and spatial aspects of a submarine design. For a conceptual design, it is sufficient to keep three spatial balances: volume, area and length in order to determine the required space in the submarine. The prototype also shows that new knowledge can be added and changed to perform new design tasks, without disrupting the existing knowledge. The questions and way to solve design problems during the exploration process can be adjusted, even reversing answer and problem is possible. However, understanding the sequence of design tasks is essential as alternative ways often results into ‘insufficient information available for solving the problem’ as the wrong design relations are selected.
SAMENVATTING

Een concept exploratie model voor het ontwerpen van onderzeeboten, waarbij gebruik wordt gemaakt van kennisgebaseerde technieken

Het conceptuele ontwerp is de eerste fase in het ontwerpproces waarbij zowel het ontwerpprobleem als de wijze waarop het probleem opgelost moet worden, niet precies vaststaan. Het meest veelbelovende concept moet ontwikkeld worden, dat voldoet aan een gestelde specificatie. Het probleem hierbij is echter dat tijdens de voortgang van het ontwerpproces meer informatie beschikbaar komt, waardoor het mogelijk is dat ofwel nieuwe vragen ontstaan ofwel de oorspronkelijke probleemstelling verandert. Als gevolg van het feit dat tijdens het ontwerpproces een verscheidenheid aan vragen kan opkomen, is het niet zinvol een vaste procedure te doorlopen. Om deze reden is gekozen voor het kennis-gebaseerde systeem QUUESTOR, ontwikkeld door MARIN. Eén van de belangrijkste kenmerken van een dergelijk systeem is, dat het onderscheid maakt tussen de numerieke kennis, die door parameters, relaties en voorwaarden wordt weergegeven en de wijze waarop deze kennis wordt gebruikt om de prestaties van een concept te voorspellen.

De conceptuele ontwerpfase van een onderzeeboot is ingewikkeld, omdat de relatie tussen het concept en de prestaties van het ontwerp niet altijd duidelijk is. Door een bepaalde karakteristiek te veranderen kan een prestatie verbeteren, maar een andere verslechteren. Om deze reden wordt bij traditionele ontwerptechnieken een nieuw concept gebaseerd op goed gedocumenteerde bestaande ontwerpen. De prestaties van deze concepten worden berekend door gebruik te maken van een model waarin zowel input als output niet kunnen worden gewijzigd: de zogenaamde "directed network"-benadering. Systemen die een dergelijke benadering gebruiken bij het ontwikkelen van een groot aantal conceptontwerpen, worden traditionele Concept Exploratie Modellen genoemd. Deze traditionele systemen hebben twee belangrijke beperkingen:

- **Beperking van de creativiteit** - Het conceptuele ontwerp wordt gekenmerkt door een intensieve dialoog tussen de klant en het ontwerpteam. Tijdens deze dialoog komen meerdere soorten vragen op, die verschillende ontwerpbeschrijvingen en berekeningen vereisen. Dit betekent dat de controle op het ontwerpproces data-gestuurd zou moeten zijn. Dit in tegenstelling tot de procedure-gestuurde controle in traditionele systemen. In traditionele systemen zijn de ontwerpmodellen en de toepassing van deze modellen niet gescheiden. Vaak zijn de
geïmplementeerde modellen niet eens zichtbaar voor de ontwerper. Dit heeft tot gevolg dat het oplossen van nieuwe ontwerpproblemen en/of toepassen van nieuwe ontwerpkenis moeilijk en kostbaar is.

- **Ontwerpkenis wordt alleen op numeriek wijze toegepast** - Alle ontwerpkenis wordt numeriek weergegeven. Een ruimtelijke indeling kan daardoor slechts door numerieke kennis gemodelleerd worden, waardoor de geometrie en topologie van het concept niet eenvoudig kunnen worden gewijzigd.

Om deze beperkingen te omzeilen wordt een "un-directed network"- benadering gebruikt, waarbij de ontwerpmodellen, die nodig zijn voor dit ontwerp, worden beschreven met behulp van numerieke, geometrische en topologische kennis. In dit proefschrift worden de belangrijkste punten beschreven, die van belang zijn tijdens de ontwikkeling van een op deze benadering gebaseerd conceptueel ontwerpgeredschap. Elke stap in het ontwikkelingsproces is onderzocht: het identificeren van het probleem, het verkrijgen van inzicht in het ontwerp en zijn structuur, selecteren van kennisbronnen en de ontwerpkenis uit deze bronnen vergaren, het selecteren van de ondersteunende gereedschappen, de implementatie van de kennis in het gereedschap, het verifiëren, evalueren en toepassen van de geïmplementeerde kennis. Het ontwikkelingsproces dat leidt tot een conceptueel ontwerpgeredschap is beschreven voor het conceptontwerp van onderzeeboten met een onderwater deplacement tussen 1000 - 3000 [ton]. Het resultaat van het onderzoek was dat veel kennis over meerdere ontwerpaspecten van onderzeeboten werd verkregen.

Het ontwikkelde prototype, SUBCEM genaamd, laat zien dat het gereedschap in staat is de grootte en de prestaties van onderzeeboten te voorspellen in de conceptuele fase van het ontwerpproces. De ontwerper kan zich concentreren op het algemene ontwerpproces. De details kan hij overlaten aan de specialist die de kennis heeft geïmplementeerd. Omdat het concept exploratie model in staat is de numerieke en ruimtelijke aspecten van het ontwerp van een onderzeeboot te integreren, kunnen ontwerpalternatieven, waarin verschillende componenten en/of layouts worden toegepast, beter onderzocht worden. Voor een conceptueel ontwerp blijkt het bijhouden van drie ruimtelijke balansen: volume, oppervlakte en lengte, voldoende om de vereiste ruimte in de onderzeeboot vast te kunnen stellen.

Het prototype laat verder zien dat nieuwe kennis aan het gereedschap toegevoegd en veranderd kan worden om nieuwe ontwerptaken te kunnen uitvoeren, zonder de bestaande kennis te verstoren. De vragen en de wijze waarop ontwerpproblemen opgelost worden, kunnen aangepast worden, zelfs het omkeren van antwoord en vraagstelling is mogelijk. Wel is vereist dat de ontwerper de volgorde van de ontwerptaken begrijpt. Als de ontwerper de verkeerde ontwerpmodellen selecteert, zullen alternatieve vraagstellingen vaak onoplosbaar blijken.
DANKWOORD

Het is een goede gewoonte dat in een proefschrift behalve de resultaten van het verrichte onderzoek ook de bijdragen van de betrokken mensen erkend kunnen worden. Doordat vele mensen gedurende het onderzoek op allerlei wijzen aan het uiteindelijke resultaat hebben bijgedragen, wil ik alle betrokkenen hierbij graag bedanken voor hun tijd en inzet.


Doordat vele aspecten een belangrijke rol spelen in het onderzeebootontwerp, zijn deelaspecten geanalyseerd en beschreven door een groot aantal studenten. De bijdrage van Klaus Deleroi, Sjouke Sipkema, Hjalmar Groen, Robert van Kuilenburg, Jan Willem de Wit, Harold Claessens, Eugene Pel, Jeroen van Diermen en Stein Daniels worden door mij zeer gewaardeerd. De resultaten van hun inzet zijn tot uitdrukking gekomen in de kwaliteit en kwantiteit van het ontwerpmodel.

Een ontwerpmodel is pas praktisch toepasbaar als deze geïmplementeerd is in een geschikt gereedschap. Al in het eerste jaar van het onderzoek heeft Martin van Hees van het MARIN zijn bereidheid kenbaar gemaakt tot het verstrekken en aanpassen van het door hem ontwikkelde kennis-gebaseerde ontwerpgereedschap ‘QUAESTOR’. De naam, die staat voor de schatkist bewaarder van het antieke Rome, geeft precies de kracht van het gereedschap weer: namelijk dat kennis waardevol is en daarom bewaard en beheerd dient te worden. Ik heb veel waardering voor zijn inspanningen en zijn grote bereidheid om vele jaren samen te werken aan de verbeteringen van het gereedschap.

Naast de implementatie van ontwerp kennis in QUAESTOR zijn ook vele jaren besteed aan het implementeren van algoritmen voor de bepaling van de vereiste ruimte. Studenten van de Hogeschool Brabant hebben dit mogelijk gemaakt. Met name het enthousiasme van Valentijn Makkenze, Marc Langeveld, Arjan Jongmans, Piet van Duuren, Mark van Roseveld, Patrick van Schelstraete, Sander Stevens, Ronald de Waal en Miranda Seters waren voor mij een grote steun.

Na het schrijven van het proefschrift hebben een groot aantal mensen zowel inhoudelijk als redactioneel verbeteringen voorgesteld. Hun opmerkingen hebben de kwaliteit van
het eindresultaat verbeterd. Met name spreek ik mijn waardering uit voor Elizabeth Wilson, Rob Zuiddam en alle collegae bij NEVESBU die de tijd genomen hebben om het proefschrift door te nemen.

Ook wil ik hierbij de prettige en collegiale contacten met mijn Delftse kamergenoot Hugo Grimmelius en mijn collegae bij NEVESBU waaronder Han Holtackers en Mirek Kaminski noemen. Naast de discussies over de ontwikkeling van de ontwerpmogelijk, zijn met hen ook de genoegens van het ‘ruime sop’ in de praktijk gebracht.

Het onderzoek is tot stand gekomen door een gezamenlijke inspanning van NEVESBU, RDM submarines, MARIN en de Technische Universiteit Delft. Met name wil ik het management van NEVESBU bedanken voor de gelegenheid die me geboden is om het onderzoek af te ronden.

Tenslotte wil ik mijn grootste en warmste waardering uitspreken voor de ondersteuning en het geduld van mijn vrouw Yvanka en onze dochter Vivian.

Het project is uitgevoerd onder begeleiding van de onderzoeksschool TRAIL" (serienummer van proefschrift: T99/1) en is gedeeltelijk gesponsord door de Nederlandse stichting voor gecoördineerd maritiem onderzoek (CMO), de stichting voor Nederlands wetenschappelijk onderzoek (NWO) en de stichting “prof. Kooijmans fonds”.

"TRAIL is accredited by the Royal Netherlands Academy of Arts and Sciences and is a co-operative venture in which the Delft University of Technology and the Erasmus University of Rotterdam participate.
CURRICULUM VITAE

Clemens van der Nat was born on 1st of September 1968 in Sassenheim, the Netherlands. In 1986 he graduated for Atheneum at the Willem de Zwijger College in Bussum. In the same year he began his study Naval Architecture at the department of Mechanical Engineering and Marine Technology, Delft University of Technology. During graduation for Naval Architecture he worked for one year at the Netherlands Institute for Fishery Investigations in a research project to study the effects of ship motions on the dynamic behaviour of a beam trawl. In 1991 he graduated "cum laude" for his M.Sc. degree. The following two years he participated in the Post Graduate Advanced Training and Research program "Transport Technology" at the Delft University. As part of this program the feasibility of a Concept Exploration Model, implemented in a knowledge-based system, was investigated. After graduating for this program, he continued working on the conceptual design system as a Ph.D. student. About 20 students were involved from different institutes and with different professions like naval architecture, mechanical engineering, electrical engineering and software engineering.

Since 1996 he joined the ship design office NEVESBU in The Hague. Being part of the forward design team he was involved in the design and specification of several submarines and offshore vessels.