THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

A Novel Submarine Design Method

Based on technical, economical and operational factors of influence

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”Writing a book is an adventure; to begin with it is a toy and an amusement, then it becomes a master, and then it becomes a tyrant; and…just as you are about to be reconciled to your servitude – you kill the monster and fling him…to the public.”

Winston Churchill

Abstract

The thesis work, with the openly published journal and conference papers, is motivated by the ambition to interact over time with the scientific community in the development of a novel coherent submarine design method to regain momentum in Swedish submarine computer aided Simulation Based Design (SBD). The work was initially stimulated by an early observation in our submarine engineering community, that the existing knowledge of naval architecture and systems theory including cost prediction and operational analysis was not coherently utilised for the design of Naval Integrated Complex System (NICS), hence the need for a coherent approach. The work is based on the idea that a coherent method works better by generating reliable information for the decision makers early in a project. The problem was to develop a user-oriented method that fully utilises existing knowledge in the submarine engineering community and reaches acceptance by submarine design engineers and the customers and recognition from the scientific community.

There are four main contributions to the coherent method in this thesis. *Firstly*, there is an integrated domain driven design approach for a technical description of the design object, the related system cost and system effect. *Secondly*, the uses of a generic design object to stimulate the operational analysis simulation and from there extract tactically driven system functions and requirements. *Thirdly*, the use of a synthesised operational environment, i.e. a war gaming event based Monte Carlo operational analysis simulation model including tactical and behavioural rules in establishing design objects system effectiveness under diverse conditions. *Fourthly*, the utilisation of the combined set of tools in the coherent method provides the designer with the possibility to generate, explore and analyse and evaluate a large number of competing feasible Play-Cards and concepts in search of the best satisfying designs.

The work has resulted in a parametric and concept exploration model for submarine design including a model for cost calculation. A simulation model with an event based and Monte Carlo operational analysis is supporting the systems analysis for evaluation of a complete submarine system. The coherent method with its models and methods provides an integrated computation and analysis environment for efficient work in the early phases and to develop the design objects from needs to a complete concept for further development during the preliminary design phase. The coherent method makes it possible to search for best satisfying designs in the identified design room within the design space by working with models in the functional domain, based on identified needs and deduced and designed requirements aggregated in a representation of a submarine, the Play-Card with its system functions and functional volumes. In a broader aspect, the same methodology can be adapted to handle integrated complex systems in general e.g. ships and airplanes.

The methods used in the coherent method have been verified in several steps. First by the FMV/FOI development team based on control calculations of the methods based on accepted theories, the model tests and acceptance and full scale test reports. The methods have also been examined and validated by design teams at industry and research institutions. In all cases, this has led to successful results with a high compliance to verifiable values and the coherent model has been proven useful for its purpose in the early phases.

Keywords; submarine system design, synthesised design model, parametric and concept exploration models, functional and mission analysis, cost estimation, operational analysis, system effectiveness, systems analysis

Preface

This work has been carried out as an industrial PhD. project and supervised by the Division of Marine design, Department of Shipping and Marine Technology at Chalmers University of technology (Chalmers) in close cooperation with, and sponsored by the Swedish Defence Material Administration (FMV), supported by the Swedish Defence Research Agency (FOI) and the major parts of the Swedish submarine industry; Kockums and SSPA. The work was initiated by the need to develop modern computer-based methods for submarine design to the submarine Project 2000 that started in 1987. The initial work has taken place at Chalmers, FMV and FOI, where it was carried out under orders from head of Submarine Bureau, Chief Engineer Björn Berg during the beginning of the Submarine 2000 project. It was carried out in close collaboration with the head of the submarine Project Section, later head of the Submarine Bureau, Chief Engineer Henrik Bohm and his team and with Chalmers under supervision of my good friend Adj. Professor Herbert Nilsson.

The final part of the PhD. project was sponsored by FMV by the Director General Gunnar Holmgren, Director Naval Systems Andreas Olsson, Head of submarine department Håkan Söderstedt, and Chief of submarine development Jan Westas and Robert Fedor. They made it possible for me to complete this effort.

The diversity of information that the author based the work on have mainly come from Kockums in Malmö with the support from the Submarine architects and engineers Kjell Hellqvist, Pär Dalander, Lars-Erik Larsson, Roger Berg, P-O Hedin, Ronny Andersson and Henrick Olofsson. Most of the tactical information has come from the Submarine Service, where the submarine officers Bo Rask, Anders Järn, Mickael Hahne, Anders Wennerström and Lars Nordenberg in an inspiring way shaped my view of the deepest features of submarine tactics. In the usual submarine engineers way, I also want to thank the "opposing side", they who sails on the surface; Lars Salomonsson, Göran Larsbrink and Göran Bark for your tireless energy in trying to broaden my periscopic view of life. Thank you for your constant encouragement.

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Throughout the work, my supervisor Professor (emeritus) Anders Ulfvarson has in a personal way supported both the author himself and the development of the work. I would also like to extend my gratitude to my chief supervisor during this endeavour, Professor Jonas Ringsberg, head of Marine technology, for his invaluable support. Thank you very much both of you.

This thesis is dedicated to my wife and son, Karin and Magnus, for your constant support and encouragement throughout the challenges I have faced pursuing my PhD.

Chalmers and FOI in December of 2014

Mats Nordin
Submariner

List of appended papers

Paper A Nordin, M., *Overview of a Methodology for the Early Phases in Systems Design of Future Submarines*, pp. 123-133, RINA Warship 2011: Naval Submarines and UUVs, 29-30 June, Bath, UK, 2011. ISBN 978-1-905040-86-5

Paper B Nordin, M., *A Functional Approach to Systems Design of Submarines during the Early Phases*, Naval Engineers Journal, Volume 127, Issue 2, June 2015.

Paper C Nordin, M., *Operational Analysis in Systems Design of Submarines during the Early Phases*, accepted for publishing by International Journal of Marine Engineering, RINA, 2014.

Paper D Nordin, M., *In Search of the Best Design – a Systems Analysis Methodology for Submarine Design*, pp. 7-18, RINA Warship 2014: Naval Submarines and UXUVs, 18-19 June, Bath, UK, 2014. ISBN 978-1-909024-28-1

Paper E Nordin, M., *In Search of the Best Design – the V-model adapted for a Coherent Design Methodology for Submarine Design*, pp. 287-297, IMarEST 12th International Naval Engineering Conference and Exhibition, INEC 2014, 20-22 May, Amsterdam, NL, 2014.

List of additional scientific papers and publications related to this thesis and work

The author of this thesis is the author or co-author of the following peer-reviewed papers:

Nordin, M., A system analysis tool for submarine design used during the study and predesign phases, Paper 21,Volume 3(3), U90 International Conference on Submarine Systems, 7-10 May, Stockholm, 1990. ISBN 91-22-01400-4

Almgren, M. & Nordin, M., Acoustic target strength of submarines, Volume I, Paper 10, RINA, Warship 91, International symposium on Naval Submarines 3, 13-15 May, London, 1991.

Nordin, M. & Almgren, M., Submarine radiated noise prediction and assessment, Paper 23, pp. 272-287, U92, International Conference on Submarine Systems, 2-5 November, Stockholm, 1992. ISBN 90-630-1664-8

Allenström, B., Johnsson, C-A. & Nordin, M., The hunt for a silent propulsor, Paper 25, pp. 327-338, International Conference on Submarine Systems, 2-5 November, Stockholm, 1992. ISBN 90-630-1664-8

Almgren, M. & Nordin, M., Submarine target strength predictions and assessment, Paper 22, RINA, Warship 93. International Symposium on Naval Submarines 4, 11-13 May, London, 1993.

The author of this thesis is the author or co-author of the following thesis and reports:

Nordin, M., *A systems theoretical methodology for Naval Integrated Complex Systems*, Thesis for the degree of Licentiate of Technology, Chalmers University of Technology, Göteborg, 2009. ISSN 1652-9189

Nordin, M. & Garmelius, M., A comparative Study on the results from the parametric study programme TC 117A, SubParm and built submarine. Swedish Defence Research Agency, FOI-R--3886--SE. ISSN 1650-1942, 2015.

Nordin, M., Garmelius, M., & Bossér, L., A comparative study on the seamlessness between the parametric based design programmes SubParm and SubDes compared to build submarines, Swedish Defence Research Agency. FOI-R--3887--SE. ISSN 1650-1942, 2015.

Nordin, M. & Garmelius, M., Cost estimation, prediction and risk analysis in the early phases of submarine design. Swedish Defence Research Agency. FOI-R--3888--SE.
ISSN 1650-1942, 2015.

Bossér, L. & Nordin, M., SubSig reflector model. A method for estimating the acoustic target strength of submarines. Swedish Defence Research Agency. FOI-R--3666--SE.
ISSN 1650-1942. May 2013.

Bossér, L. & Nordin, M., SubSig radiated noise model. A method for estimating the radiated noise of submarines. Swedish Defence Research Agency. FOI-R--3889--SE. ISSN 1650-1942, 2015.

Bossér, L. & Nordin, M., SubSig magnetic signature model. A method for estimating the induced magnetic field of submarines. Swedish Defence Research Agency. FOI-R--3890--SE. ISSN 1650-1942, 2014.

Contents

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Glossary and abbreviations

This thesis uses a considerable number of terms in perhaps slightly different ways due to the cross-disciplinary characteristics of naval architecture and ship design, especially when not only technical factors of influence are used, but also economical and operational factors of influence. Hence, a list of definitions is provided as a guideline and reference to the reader.

- **2.5D**. A 2D drawing but with the related depth or width implicitly given or defined mathematically. A 2.5D drawing can generate a 3D model when a 3D CAD programme is used.
- **Best design**. In this report the phrase “best design” refers to a feasible and balanced Play-Card or concept that meets the customers and stakeholders preferences and has been chosen by them as a result of initial design.
- **Best designs**. In this report the phrase “best designs” refers to a set of feasible and balanced Play-Cards or concepts that meet the customers and stakeholders preferences and thereby has been accepted and preferred by them as a result of initial design.
- **Calculation element**. An element calculated from Data elements and Measured elements, which can be included in MoE or MoC, from an operational analysis simulation
- **Coherent design method**. In this report, a coherent design method encompasses the steps from early needs to the selection of best designs, based on technical, economical and operational factors of influence.
- **Concept**. A concept is a possible solution to stated needs.
- **Concept design model**. The submarine concept design model SubDes.
- **Configuration**. An arrangement of parts or elements in a particular form, figure, or combination.
- **Data element**. Is any Design parameter, Design relation or Measure of performance, or any other technical information from a design object.
- **Design area**. An identified area in a Design room where there exists several, at least two, Design points.
- **Design object**. An initial concept, i.e. a Play-Card, or a concept, depending on where in the design process we are during initial design.
- **Design point**. A specific set of parameters representing a point in the Design room.
- **Design room**. An identified sub-space in the infinite Design space for submarines.
- **Design space**. The space of all possible combinations of design parameters, i.e. an infinite design space.

- **Designing requirement**. In this report the designed requirements are formulated when initial operational needs have been validated in a feasible and balanced Play-Card or concept. Thus the requirements can be referred to as being designed.

- **Function**. An action for which something is specially fitted or used, a purpose. Generally this is expressed as a verb phrase e.g. "provide propulsion" or "generate electrical power". In some cases it is more natural to use a noun.

- **Functional requirement**. A requirement on a system referring to its intended use or action, formulated in the functional domain.

- **Functional volume**. A rule-based scalable volume, including service, shock and general volumes, for a system function with selected system principle and needed performance. The functional volume has associated weight, cost, power consumption etc., manifesting what is needed in order to perform the system function, i.e. the functional volume embrace the envelope of possible systems solution for a selected system principle.

- **Functions/functional domain**. The domain where needs are translated to initial requirements with the help of a design objects designed in a generic design model, following the Swedish nominal design process.

- **Generic design object**. An initial concept, i.e. a Play-Card.

- **Generic submarine model**. A synthesised model of a submarine in the functional domain. A style can be set with a physical form that is packed with necessary system functions and related functional volumes. Submarine Play-Card exploration and parametric variation studies are performed with the help of this model, i.e. SubParm.

- **Initial cost requirements**. A given cost level based on calculations made prior to, or during initial design.

- **Initial design**. The design process from initial operational needs to the selection of a preferred concept prior to preliminary design, i.e. to the selection of best designs.

- **Initial operational needs**. Defined by Concept of operations (CONOPS) and Why, What, Where and How statements during mission analysis.

- **Initial requirements**. These contain initial operational, technical and cost requirements.

- **Initial technical requirements**. Developed and deduced from initial operational needs through the help of mission analysis and design of initial concepts, i.e. Play-Cards.

- **Installations domain**. The domain where the chosen systems and systems solutions are designed in more detail, usually during the systems and detail design phase, i.e. after the preliminary design phase, following the Swedish nominal design process.

- **Measure of capability**. The quantitative measure of the system capability based on individually adapted combinations of Data elements, Measured elements and Calculation elements for the relevant mission type.

- **Measure of effectiveness**. The quantitative measure of the system effect based on individually adapted combinations of Data elements, Measured elements and Calculation elements for the relevant mission type.

- **Measured element**. An element, measured during an operations analysis simulation.

- **Mission analysis**. The process of clarifying Initial operational needs by deducing and developing a set of initial requirements to start the Initial design process.

- **Mission type**. Distinctive mission for submarine. In this report ten defined mission types are described.

- **Needs**. A statement of needs comes from higher strategic and operational staff and is usually presented by the customer including the stakeholders, and forms the starting point for initial design.

- **Needs domain**. The domain where the focus is on why, what, where and how something needs to be done. This includes description of concept of operations, CONOPS, and any other description connected or related to the system in focus, following the Swedish nominal design process.

- **NICS**. Physically large naval integrated and complex systems such as surface warships and submarines.

- **Play-Card**. An initial concept that is feasible and balanced, representing a submarine, where the designer has set a style that generates an arrangement populated with functional volumes. The Play-Card is used as a budget for concept design.

- **Redesign**. To create a submarine from its original initial requirement without necessary following the original style, general arrangement or performance with the aim of designing something better than the original design.

- **Reengineer**. To recreate a submarine from its original building specification without changing style, general arrangement or performance

- **Script**. A parametric rule-based set of properties describing a specific system function, system, or installation.

- **Seamless transition**. A transition between the different domains without more than minor changes, usually less than 5% in general, to the main characteristics or performance of the submarine design object.

- **Style**. A particular kind, sort, or type, with reference to form, appearance, or character set by a designer.

- **System design**. Design of a system as a whole, i.e. a ship or submarine.

- **System effect**. The result of a system having done its work, tasks or mission.

- **System effectiveness**. The quantitative result of a system having done its work, tasks or mission. See also MoE.

- **System function**. A spatial object for an intended use and preferred action, selected system principles and characteristic performance. See also Functional volume.

- **System Function Structure (SFS)**. SFS is an aggregation of system functions based on functional decomposition of several built conventional submarines equipped with ADP or AIP. A catalogue of needed and possible system functions that can be used to build up a conventional submarine.

- **System of systems**. In a modern defence system, a submarine is a component, a system in itself but one of several systems in a navy. As a system of systems, a submarine consists of several systems.

- **System philosophy**. Part of a design philosophy that has been developed over time and that reflects national experience and best-practice of submarine design, including international influences.

- **System principle**. An intermediate step between function and system solution, e.g. a system for propulsion can use different principles to do the work, such as electric drive, hydraulic drive, pneumatic drive or mechanical drive.

- **System solution**. A solution to a functional need and chosen system principle, e.g. a propulsion system with the system principle of a DC motor with a specific layout as a solution for the system**.**

- **Systems domain**. The domain where the systems and systems solutions are chosen and designed at the systems level, usually during the conceptual and preliminary design phases, i.e. after the study phase, following the Swedish nominal design process.

A	Activity (Local activity within the complete submarine)
ADP	Air Dependent Propulsion
AIP	Air Independent Propulsion
ASW	Anti-submarine warfare
ASuW	Anti-surface warfare
CE	Calculation Element in operational analysis
CONOPS	Concept of Operations
DE	Data Element in operational analysis
DP	Design Parameter
DV	Design Variable
FA	Functions Analysis
FAT	Factory Acceptance Test
FBS	Functional breakdown structure
FMV	Swedish Defence Material Administration
FOI	Swedish Defence Research Agency
FSA	Foreign secrecy act
FCSA	Foreign commercial secrecy act
GA	General Activity for the complete submarine
GUI	Graphical user interface
HAT	Harbour acceptance test
HTU	Half time upgrade
LCC	Life cycle cost
MBSE	Model Based Systems Engineering
ME	Measured Element in operational analysis
MIMI	Naval installation breakdown structure
MoC	Measure of Capability
MoE	Measure of Effectiveness
MOGO	Multiple-Objective Genetic Optimisation
MoP	Measure of Performance
MoR	Measure of Risk
NICS	Naval Integrated Complex Systems
NOP	No longer operational
NOB	Not built but fully designed
NSA	National secrecy act
NFSA	National and foreign secrecy acts
OA	Operational Analysis
OEM	Operational Effectiveness Model
OMoC	Overall Measure of Capability
OMoE	Overall Measure of Effectiveness
OR	Operational Research
OSI	Open source information
PA	Planned Activity (Local activity within the complete submarine)
PGA	Planned General Activity for the complete submarine
SA	Systems Analysis
SAT	Sea Acceptance Test
SBD	Simulation Based Design
SBS	System breakdown structure
SE	Systems Engineering
SFS	System Function Structure
SLOC	Sea-Line of Communications

SS	Submarine in general
SSA	A conventional auxiliary submarine, e.g. a submarine used for undersea research
SSC	Conventional submarine coastal
SSG	A conventional submarine equipped with guided missiles
SSK	Conventional submarine
SSW	Conventional submarine midget
SubAn	Submarine design and analysis toolbox
SubCoeff	Sub-module for calculation of submarine hydrodynamic derivatives
SubCost	Submarine cost calculation module for cost and risk management for Play-Cards and concepts
SubDes	Submarine design module for concept design of submarines
SubEn	Sub-module to SubParm and SubDes for power-energy design
SubFunc	Submarine mission analysis module for identifying and deducing initial requirements
SubHydro	Sub-module to SubParm and SubDes for static and dynamic stability including trim polygon for tank contents, consumables and weapons and Pay-loads
SubMan	Sub-module to SubParm and SubDes for manoeuvring and seakeeping design
SubParm	Submarine design module for Play-Card design of submarines in the functional domain
SubPow	Sub-module to SubParm and SubDes for drive-line and energy storage design
SubPred	Sub-module to SubParm and SubDes for speed-power predictions and propulsor design
SubRec	Sub-module to SubParm and SubDes for emergency recovery manoeuvre design
SubOA	Submarine operational analysis module for Play-Card and concept system effectiveness evaluation
SubSA	Submarine systems analysis module for analysis and evaluation of Play-Cards and concepts from technical, cost and system effect factors of influence
TA	Tactically driven Activity (Local activity within the complete submarine)
TF	Tactical Function
TGA	Tactically driven General Activity for the complete submarine
TOC	Total Ownership Cost
VF	Functional Volume
VoV	Verification and Validation
VR	Reference Volume

1. Introduction

Classical naval ship development methods for surface combatants and submarines have by and large been similar during most of the 20th century and only begun to change with the start of the Polaris programme in the 1960s. A submarine project was synthesised, calculated and redesigned until the necessary balances for the submarine were achieved. New ideas were implemented in steps and to move forward in the development process, the design was gradually "frozen" at different times in order to consolidate design choices and to reduce uncertainties, with the side-effect that the creativity and therefore alternative routes was limited early in the project. With long development times, this often resulted in systems that were obsolete already on delivery. This chapter describes the issues and rationale for a necessary development of the design process by using not only technical and economical factors of influence but also integrating operational analysis into the process in a coherent way.

This thesis deals with the scientific advancement of design methods in the early phases for Naval Integrated Complex Systems (NICS) exemplified by military submarines, Nordin (1990 & 2009). With design we mean not only the technical and cost aspects, but also tactical performance, and system effect, i.e. the result when using the system for its intended purpose, following Nordin (1990 & 2009) and Kormilitsin & Khalizev (2001).
Especially three words are emphasised here:

- *Naval*, because these are physically large systems, often produced in only a few units and usually without any previous prototype. This puts great demands on the design process from the very beginning, including risk mitigation and handling.
- *Integrated*, as several functions are aggregated but in a more integrated system, often with secondary[1] redundancy, which means that other systems can perform the function.
- *Complex*, as the total system must solve several different tasks and roles, often during the same mission, and where functions and their functional requirements cannot be found with direct methods.

The multi-disciplinary aspects of ship design in the early phases following the holistic perspective of naval architecture, i.e. a system of systems for physically large and complex system, has been described by Andrews (1998, 2011b & 2013). This also includes some of the new complementary views on Systems Engineering, with its roots in software, computers and electronics, given by Van Griethuysen (2000), which can be described as:

[1] As opposed to primary redundancy which means that the function in focus is designed with its own redundancy, i.e. a parallel solution within its own systems solution.

- The focus on engineering as the creative heart of management of projects.
- The need to develop a greater variety of practical tools suitable for real situations, products and technologies.
- A complementary view to the physically large system regarding the techniques and insights to be learnt in the area of requirements rich process/information systems.
- To encourage careful planning of the testing and integration process, including the need to trace requirements through the design process to acceptance which goes beyond the traditional (lack of) emphasis in teaching of "design management".

Naval architecture and systems engineering have some differences in their approach. Modern Ship design focuses on top-down development of physically large and complex system that is to be made feasible by requirement elucidation, Andrews (2011a), whereas System engineering has a closer relationship to engineering design, Hubka & Eder (1982), Hubka & Eder (1988) and Pahl & Beitz (1996). In reality this means the design of valid requirements by modelling the ship system with its systems iteratively level by level following Nordin (2009). This design effort, with its compromise between requirements and physical design, including affordability, has the aim of satisfying not only the design team but also the customer and stakeholders' needs. This stands in contrast to the risk of over-elaboration of requirements in computer databases, under the banner of "requirements engineering", without progressive design modelling to establish feasibility in terms of cost and in-service date according to Van Griethuysen (2000). The risk of over-defining requirements in documents is imminent.

Ship design is a process to develop a design description for a feasible ship to a level sufficient for its production, where its properties and capabilities correspond to an expected behaviour in one or more specified operational conditions. The design description, initially also called a concept, contains information about the style, size, arrangement, performance and cost of the ship and its systems and components from which technical performance is obtained. Relevant performance depends on the tasks that the ship shall perform. This multifunctional nature of the design problem hampers a more direct design process to develop a design description to such a level of detail that it can serve as the basis for the production of a ship. The approach with models and tools in this thesis is developed for submarine systems but is in its general structure also suitable for other integrated and complex systems such as surface ships, i.e. system of systems.

The presented coherent method focuses on the two early phases in the Swedish design procedure, i.e. the study and conceptual design phases, when the most suitable concept is defined. The purpose of the submarine coherent design process is to find this (or a few) valid concept definition of a submarine system within the intended economic budget and at least in compliance to the expected system effect. This should contain sufficient information to allow for a further refinement of the chosen concept in the preliminary design and the consecutive design and construction phases. The technical development of computer systems, both for on-board and design use, has provided new opportunities and solutions simplifying several tasks. This development, however, has not only made it easier, it has also led to significant problems with time and cost estimates for software development in sensor, command and control systems etc. In some cases, cost has accelerated in an uncontrollable way. The number of combinations of different system solutions, their cost and the possible system effects, has multiplied since the end of World War II. Problems which were relatively simple are today more multifaceted and complex to solve. Today the design space has reached such a size that it can no longer easily be overviewed, if it ever was. Causality has become increasingly more difficult to interpret. Development of coherent methods and tools for use in the early phases of NICS design is therefore necessary. According to Van Griethuysen (2000) there is a very strong interaction between the system and subsystem design levels through mechanisms such as weight and size. This puts a premium in good synthesis models of the overall design and indicates the importance of good design modelling before finalising subsystem requirements. It also indicates the importance of good estimation in allocating budgets to those responsible for developing the subsystems. There are several accounts of national design processes for ships and submarines in the literature, e.g. the US and UK design processes. As there are differences in the definitions of these phases, the nominal Swedish design process and related definitions are used in this thesis following Nordin (2009), see Figure 1. The Swedish design process prescribes and relies on continuous research and technology development in parallel with and prior to new projects in order to risk-minimise new systems development and be able to integrate more mature systems into the ship design process. This parallel R&D process has however been subject to less continuous planning than necessary.

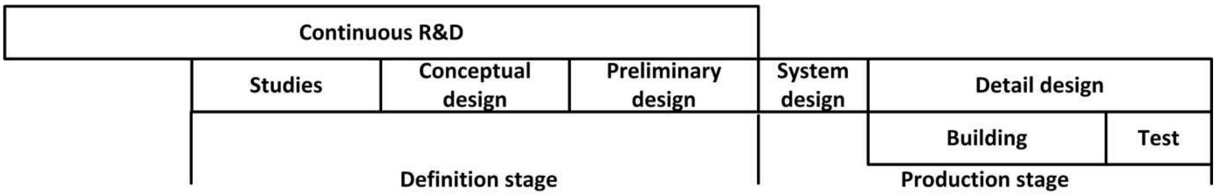

Figure 1: The consecutive phases and stages in the nominal Swedish ship and submarine procurement process.

Long term military planning and technology studies lay the foundation for system development and procurement of naval systems such as submarines. Even before a submarine project starts, military studies of force structure and concepts of operation (CONOPS) are conducted at the defence staff. As a result, directives for strategic planning and execution of R&D studies are given as well as directives for system studies for ships and submarines. Such studies can be performed with the aim of studying future alternative alleys of options or as a direct start of a submarine project based on deduced needs from CONOPS, expressed in:

- **Why** we need submarines.
- **What** they are supposed to do, i.e. tactical mission types.
- **Where** they are supposed to operate.
- **How** they are supposed to operate, i.e. mission profiles.

This thesis focuses on the two early phases of design during the project definition stage, i.e. the studies and conceptual design phases. Feasible and suitable solutions are found in the study phase and they are further developed and refined as submarine concepts during conceptual design. This work includes the following major activities:

- Development of more detailed mission driven CONOPS, mission profiles and selection of references for CONOPS, missions and systems.
- Market and technology studies and establishing procurement approach and preferred novelty of design.
- Concept exploration.
- Concept studies.
- Concept design.

The conceptual approach has been described in detail by several authors, e.g. Andrews (1986, 1998, 2011b & 2012), Brown (1998 & 2003), Van der Nat (1999), Van Griethuysen (2000), Kormilitsin & Khalizev (2001), Nowacki (2010), but particularly by Andrews (2011a & 2013) regarding requirement elucidation. A review in Nordin (2009) of the three latest completed Swedish submarine procurement projects, regarding influence on real cost outcome, clearly shows not only the importance but also the possibility to do more work in the early phases and thereby reduce errors. During the project definition stage (study, conceptual design, and preliminary design phases) only an average of 5% of the total procurement budget is spent.

According to Blanchard & Fabrycky (1998) experience has indicated that there can be a large commitment in terms of technology applications, the establishment of a system configuration and its performance characteristics and potential cost at the early stages of a program. It is at this point when system-specific knowledge is limited, but when major decisions are made pertaining to the selection of technologies, materials and potential sources of supply, equipment packing schemes and levels of diagnostics, manufacturing process, and the establishment of a maintenance approach, that costs are committed. See the curve (solid) below in Figure 2 for real cost outcome per phase as a percentage of the complete procurement for the Swedish submarine type A17 in a series of four submarines delivered between 1987 and 1990. The principal curves (dashed and dotted), illustrated in Figure 2&3 below, indicate that late changes in a project becomes disproportionately expensive due to the combination of an already high level of committed cost and the difficulty of late changes to the design. Therefore it is important to get it “right” in the early phases in a project.

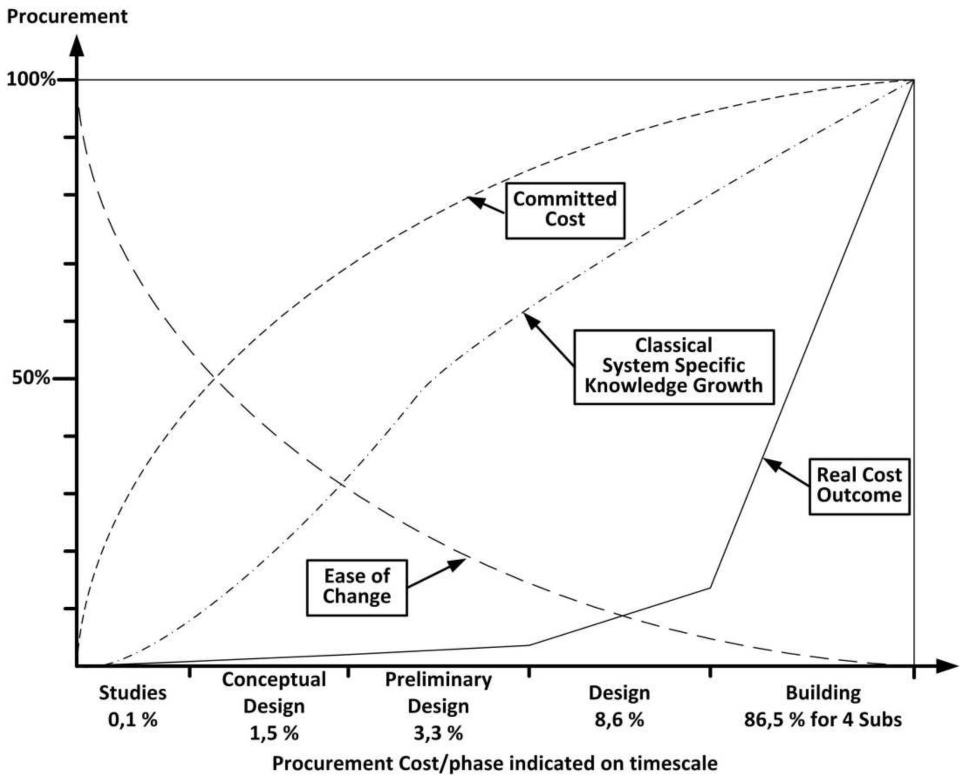

Figure 2: Classical knowledge growth in relation to influence on the design, ease of change, committed cost and cost outcomes/phase, Nordin (2009).

The analysis of previous submarine projects has shown that mistakes in the early phases where made because of inadequate handling of the primary balances (volume and weight balance, power and energy balance etc.), which gave a bad estimate of submarine size, Nordin (2009). Deficiencies were sometimes caused by incorrect instructions and the absence of early decisions on the ultimate goal but also by a lack of knowledge on the basis of estimates and predictions in the early stages. Changes and corrections in size and general arrangement caused by deficiencies in the primary balances are very costly if they are to be corrected late in the project. In the worst case this will terminate a project.

Submarine projects have by nature their greatest uncertainty in the beginning, but this is also where the affectability is highest, i.e. ease of change. To improve knowledge growth, precision, speed, and the qualitative and quantitative information in the new diversity of explorable options, a new set of tools is needed for design that can also evaluate developed options in a quantitative way, i.e. initial concepts' system effectiveness in an operational analysis tool.

The degree of influence and commitments in the different phases of procurement during a nominal submarine project based on committed cost and real cost outcome clearly shows the importance of the design activity in the early phases, as illustrated in Figure 3. The desire is of course that the affectability can be kept open as long as possible and that the proportion of committed cost can be kept down for as long as possible while ensuring that a desirable level of system specific knowledge growth can be accomplished early, a level that is in parity with or better than the committed cost.

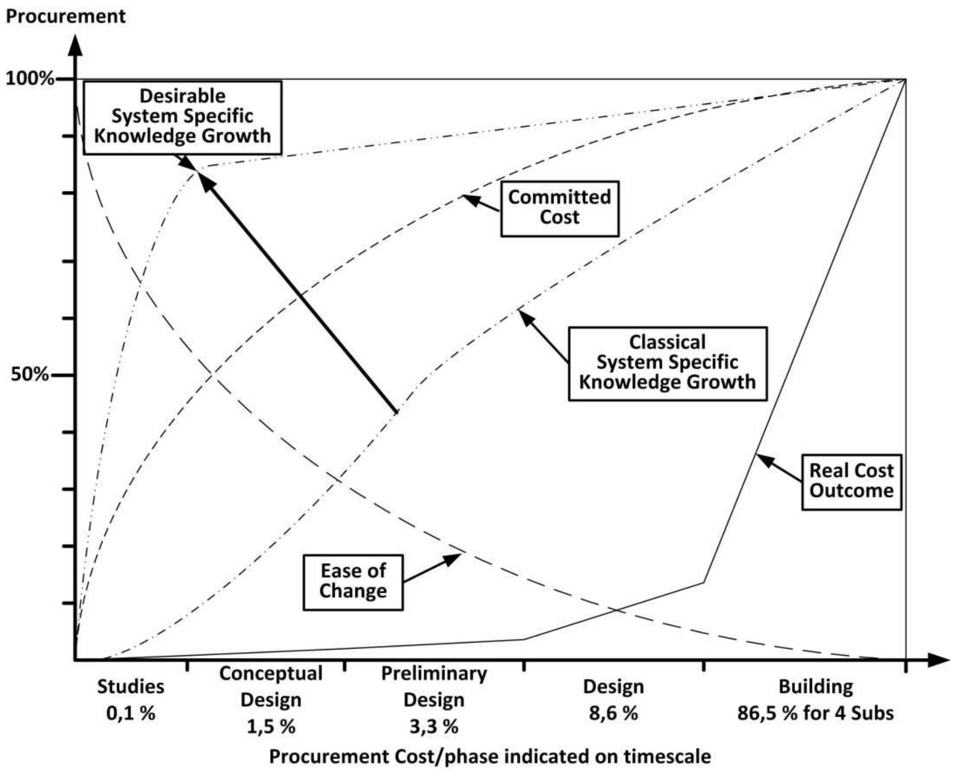

Figure 3: Desirable and classical knowledge growth in relation to influence on the design, ease of change, committed cost and cost outcomes/phase. The thick arrow shows a desirable move of the "Classical Systems Specific Knowledge Growth" to development with much more knowledge in the early phases, Nordin (2009).

The aim was therefore to develop a coherent model based on the original idea from 1987 presented by Nordin (1990) that was based on Andrews (1986) and studies performed according to Van der Nat (1999) and Nordin (2009) and to use the holistic perspective of naval architecture and complemented by systems engineering, with technical, economical and operational factors of influence with which:

- We can develop projects with emphasis on the early phases.
- We allow for an early knowledge growth, i.e. a steeper growth and reach a higher level of system specific knowledge without having a negative impact on creativity.
- We do not restrict ship designers too early and to avoid directly basing the design on older systems solutions.
- We generate reliable information for decision-makers and stakeholders.

It is vital for a successful design that early predictions of size and the primary balances of a submarine design object are correct, as has been shown by several studies reported in, e.g. Nordin (1990), Burcher & Rydill (1994), Andrews et al. (1996), Van der Nat (1999), and Kormilitsin & Khalizev (2001). A more developed design method, which reduced the early sequential approach by the use of a more parallel approach, was introduced with the development of concurrent engineering for ship design, e.g. Mistree et al. (1990).

If the proposed coherent method is adopted, then it is believed that a designer can exploit, develop, process and analyse and evaluate in a systematic way not only current knowledge but also novel alternative approaches. This coherent method would also provide the ability to manage the large amount of existing technical, economical and operational information, in an integrated way at different levels of abstraction in such a way that experienced submarine designers can recognise it and take advantage of this information for requirements elucidation following Andrews (2011a & 2013). According to Nordin (2009), this also means that it is possible to design the requirements through the study and conceptual design phases by architectural modelling of Play-Cards and concepts. By the iterative procedure we not only design new feasible and balanced submarine concepts, but actually design a balanced set of affordable cost-efficient requirements.

The intention of the proposed coherent method is to reduce the effort required to generate and evaluate a large number of alternative submarine designs during the exploration of the design space in the early design stage of submarines. This is achieved in spite of introducing not only technical and cost related information, but also effectiveness information from operational analysis. The first representation of a submarine design description is in this thesis called an initial concept, i.e. a Play-Card and holds the basic necessary information of the design. A Play-Card is also the smallest feasible design solution for the stated needs. Play-Cards are used to explore the design space and several are developed in the earliest phase, i.e. in the study phase during the search for the appropriate design room. From there the search for best designs starts. Selected Play-Cards, with their budgets, will later be developed in more detail and mature to full concepts during the conceptual design phase.

A concept contains all the information necessary to describe the complete submarine system and its performance on a system level prior to the start of the preliminary design phase. The physical structure of the systems includes installations, major equipment and some components which provide the technical performance that is related to the tasks and missions that the functions of the submarine system shall be able to perform.

2. The structure of the thesis

Presents the structure of the thesis and guidelines for the reader.

The structure of this thesis is designed to reflect the development of a novel submarine design method, a coherent design method, for Naval Integrated Complex Systems, see Figure 4.

In the introduction, Chapter 1, existing knowledge of naval architecture design procedures for the early phases is complemented by systems engineering are described, but also the rationale for the work. In this Chapter 2, the structure of the thesis is explained. The Structure and this description of the thesis will also act as a guideline for the reader.

Chapter 3 describes the research objectives and research questions associated with the industrial and scientific problems as well as the methodological description, the overall approach and a description of the successive developments leading up to the synthesis of the work and development of a coherent design method with all its models and sub-models.

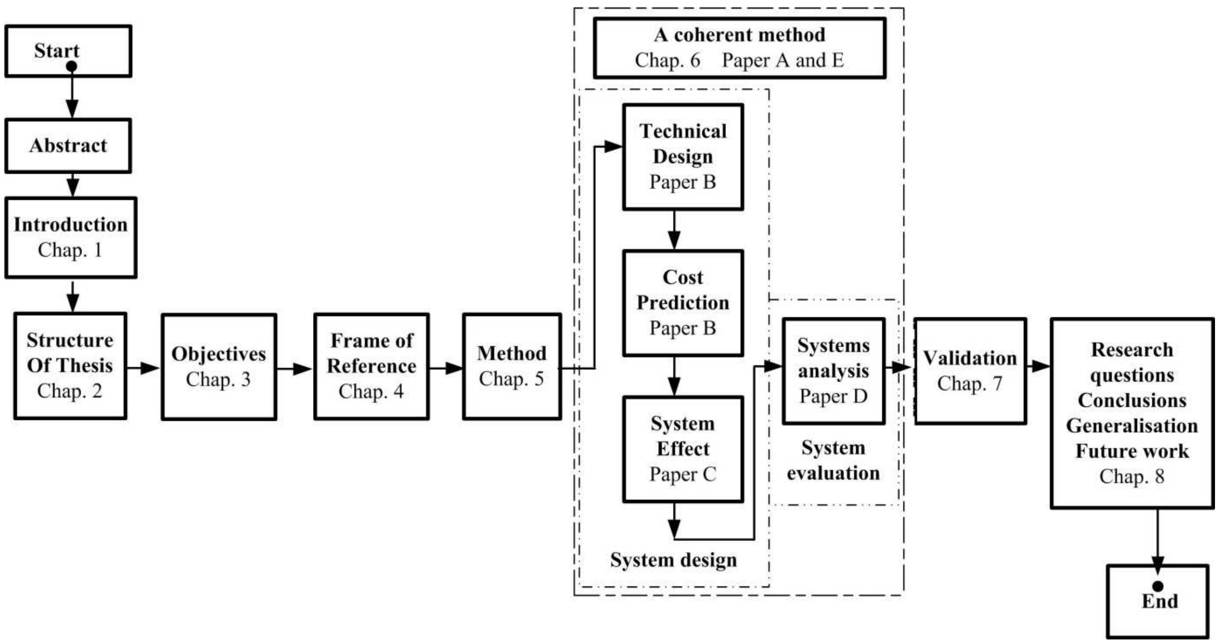

Figure 4: Structure of the thesis and a guideline for the reader.

In Chapter 4, the frame of reference, the historical development of the ship and submarine design domain including the systems view of naval architecture and the development and implementation of system design with their various models and methods are introduced.

Chapter 4 also explains the reasons why some parts of the development of naval architecture and systems engineering and operational analysis was partly ignored in Swedish submarine design before 1987. This was concluded in a study on design method and an analysis of the Swedish submarine design process, presented in Nordin (2009), and used in Chapter 3 in this thesis as a basis for the industrial problem.

Due to the length of time of my own work in this field, the frame of reference naturally includes not only international sources but also own work as it developed in dialogue with design teams worldwide as well as nationally with the Swedish design teams at FMV/FOI/Chalmers and at Kockums and SSPA. Chapter 4 illustrates how tools are used in the ship and submarine design domain.

In Chapter 5, both the practical, initially *ad hoc* approach and the later developed scientific approach of designing design tools are described from a method point of view. This also includes the practical and scientific validation process which is described and later used in Chapter 7.

In Chapter 6, the coherent method, and the included main models are described briefly. The models: technical design, cost calculation, operational analysis for system effectiveness calculations and systems analysis with evaluation and selection on a general level, are used as an approach in the search of best designs.

The result of the development of the coherent design method has been implemented in a set of tools, the toolbox called *SubAn*, *Submarine Analysis and design*. The coherent design method is detailed in the papers A, B, C, D and E. All the papers are appended to this thesis, and each are contributes to the argument of a coherent method:

A. A brief overview and the starting point for the development of a coherent method.
B. Technical design in the functional domain, including a brief resume on costing of submarines.
C. Operational analysis and the system effectiveness for submarines.
D. Systems analysis based on technical, economical and operational factors of influence in search of best design.
E. A brief summary and result of the development of the coherent design method.

In the final sections, chapters 7 and 8, the result of synthesis and its verification are discussed. This is followed by a discussion on the validation of the coherent method and its results. The final chapter contains answers to the research objectives and research questions, together with discussion, conclusions, and some suggestions for further work.

3. Objectives, relevance and limitations

Presentation of research objectives, the structure and development of work, including both industrial and scientific relevance for a coherent design method for submarine design.

3.1 Objectives of work

This thesis aims to develop the scientific basis for a coherent design method with the inclusion of a learning process that entails a result with better accuracy and content in the early phases of a project, i.e. in the definition stage. The starting point for the thesis was an early observation in our submarine engineering community by the author in June 1982 while serving at FMV Submarine Bureau: building section as a building control engineer:

Why is it that the existing knowledge of naval architecture with its systems view on system design and cost, including operational analysis, is not utilised in a coherent method for the design of Naval Integrated Complex Systems?

Hypothesis: *Develop a coherent design method based on the answers to the research questions and method issues below and show that a developed coherent method works better compared to the earlier design method.*

The hypothesis is further developed to research questions.

How can we quantify a system technical design, system cost, and system effect within the definition stage before the system in focus is designed in detail? How can we generate reliable information for the decision-maker early in a project? The following detailed research questions (RQ) can be asked. How do we know in advance, i.e. during design, before the actual system of interest is built and accepted by the customer:

- That the technical system is feasible and balanced and corresponds to the needs? RQ1
- What the system is going to cost? RQ2
- What is the system effect of the system? RQ3
- That the final design is cost effective? RQ4
- That the chosen design is the best possible design? RQ5

Important method issues were raised from the research questions above. What do we require from a method that:

- Gives continuous and traceable knowledge growth from first idea to a complete systems definition? MI1
- Generates knowledge growth with higher precision earlier than before? MI2
- Generates content with a substantial higher level of knowledge without hampering creativity? MI3
- Is both educative and explorative? MI4

Industrial relevance, i.e. practical issues

The origin for this thesis is the relevant historic Swedish submarine design procedures, where a number of deficiencies were identified and carefully analysed. These were reported in Nordin (2009) and presented below:

- Deficiencies in precision for previously used parametric design models.
- Lead time for development of concepts was too long.
- Deficiencies in the understanding whether all balances where fulfilled.
- The early deficiencies in precision continued to affect the design as the identified design room in the design space was not entirely correct.
- The early deficiencies in precision also continued to affect the precision and result in the next phases as there was no integrated information centre.
- The consequence of long development times for concepts was that too few concepts were developed and the design space was not fully explored.
- The combined consequence of deficiencies in precision for parameter sets and that too few concepts were developed was that a satisfying design point/area could not be established early enough, if ever.

Without a fully developed coherent method, a temporary effect was a return to the older type ship development method. This introduced new problems for modern designs as new capabilities were introduced resulting in an even more integrated and complex systems structure. From an industrial perspective, there is a need for a coherent design method, where the above identified deficiencies have been corrected.

Scientific relevance, i.e. modelling issues

Based on internationally published papers and publications within the design and especially the ship design domain, weaknesses were identified in the scientifically published knowledge as reported in Nordin (2009) and addressed in this work. This was especially true within six areas:

1. A coherent method for an integrated exploitation of models and methods for technical system design, system cost, system effect and systems analysis in search of “best design” of NICS.
2. A method where the result is valid throughout the consecutive phases during the definition of the product.
3. A method from needs to an initial concept via a submarine style and a parameter based synthesised design model in the functions domain. The initial result stimulates an operational analysis model for given missions. From the results of the operational analysis, system functions requirements are extracted that populates a system functions requirements matrix, which after analysis consists of an identification of the design room in the design space of submarines.
4. A model for technical system design from function, including style, to form through a Generic design model in the functions domain, the result of which can be further used in a concept design model in the systems domain.
5. A model for system effect for given mission types that has a traceability of its results back to the technical system design and its system costs.
6. A model for systems analysis of the results from the technical design, cost calculations and system effect, to clarify design drivers, design possibilities and consequences on alternative designs so that the best suitable design point(s)/area(s) can be identified and presented for decision by the decision-maker and stakeholders.

3.2 Limitations and boundaries

Any governmental and industrial organisational impacts due to the method developed in this thesis, are outside the objectives of the thesis. However, it is undoubtedly of interest for the organisation if this coherent design method is implemented and used. This thesis does not discuss design of knowledge databases but rather the use of them in design models and processes such as within the coherent design method. Due to the Swedish national secrecy act, some submarine data have been omitted without changing the results. In the same way absolute price data is presented in relative cost terms due to its commercial sensitivity.

3.3 Development of work

The submarine design project was initiated in May 1987 at the Department of Underwater Technology at Chalmers and sponsored by the FMV Submarine Bureau. This was part of an effort to regain momentum in the area of submarine design supported by computers within the area of *Simulation Based Design* (SBD). During 2001, a further need was raised, to adapt the developed method to the international standard of ISO/IEC 15288, and at the same time adapt to the naval design and procurement procedures in accordance with the approach for NICS.

The development of methods, models and tools for technical, economical and operational analysis and design existed in a first conceptual test version during spring 1990. It was named *Submarine Analysis* (SubAn) version 1.0. The toolbox, see Table 1, was briefly introduced at the International submarine conference U90 in Stockholm 1990. During the period 1990-1996 the toolbox was modified, changed and expanded gradually when new requests for functionality arose. Version 2.0 was put into operation in 1991 and version 3.0 was delivered in 1994. After the end of the Cold War, major changes were made in the Swedish defence structure. In 1996 new needs arose to further deepen and broaden the toolbox, mainly regarding the opportunities for operational analysis of a more multifaceted scale of tasks. Consequently version 6.0 was delivered in 2010. From 2011 until today, 2014, the toolbox has been expanded and refined especially with modules that allow for the search of a suitable best design including management of evaluation and selection tools. During the fall of 2014, version 9.2 was delivered after extensive verification & validation (VoV) by a participatory approach with validation teams from Kockums, FMV and FOI.

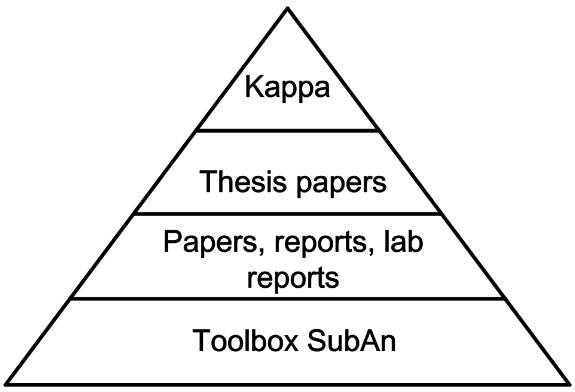

Figure 5: The structure of the complete work related to the coherent method.

The present thesis is the result of work, see Figure 5, which was initiated, managed and directed by the author. It was initially launched in conjunction with the submarine design development project and the first ideas for the Submarine 2000 project:

1987 – 1990	From a vision, a first conceptual approach and a set of methods were developed for evaluation of submarines, i.e. the concept design model SubDes and the operational analysis model called Ubat.
1990 – 1995	Tests and first use of the methods in SubAn, the models SubDes and SubOA.
1996 – 2001	Reviews of methods and external VoV of SubOA by naval officers and FOA.
2002 – 2009	Development of a coherent design method toolbox, including VoV.
2010 – 2014	Development of a coherent design method in search of best design, including VoV of the complete SubAn Toolbox, see Table 1.

The toolbox has since its first introduction in 1990, been used for several different purposes. From the development of completely new submarine concepts such as for Submarine 2000 Project (A21-A23), to the analysis of subsystems on the submarine Viking project (A24-A25), submarine type Gotland (A19K and A19S), as well as for evaluations of new components and batteries for submarines type Näcken (A14 and A14S), Västergötland (A17) and Södermanland (A17S). The toolbox has also been used for analyses of other submarines on the market. During the development of the Swedish Next Generation Submarine (NGU/A26), the software package have been used from the beginning, both as a creative tool for designing concepts by the design team and to verify the results from other computational and design tools, as well as for follow-up at the various reports from within the governmental agencies as well as from the industry. The toolbox has also been extensively used in training and education of new submarine designers, both national and international, and as a visualisation of the Swedish design philosophy. The SubAn toolbox today consists of five main modules with several sub-modules, see Table 1 below, covering a total of over 700 000 lines of code.

Table 1: The Swedish defence agencies FMV/FOI toolbox SubAn version 9.2.

SubAn: Toolbox for submarine analysis and design	
SubFunc: Functional analysis module	
SubFunc	Mission analysis tool in the functional domain, including CONOPS and mission profiles (Why, What & How)
SubMap	Generation of maps for simulation (Where)
SubDes: Design module for submarines in the functions and systems domains	
SubParm	Submarine style and parametrically based synthesised design model
SubHull	Design of hull form, including sail and rudder components etc.
SubStrength	Design of pressure hull
SubPred	Prediction of speed-power relation
SubPow	Prediction of power-energy balance and endurance
SubEn	Prediction of auxiliary power
SubHydro	Prediction of static intact stability and damaged stability
SubCoff	Prediction of hydrodynamic coefficients
SubMan	Prediction of manoeuvring and sea-keeping capability
SubRec	Prediction of emergency recovery capability (blowing, pumping, reversing etc.)
SubSig	Signature requirements and signature prediction
SubCost: Cost calculation and risk assessment module	
SubCost I	Prediction of cost elements and total cost in the functional domain
SubCost II	Prediction of cost elements and total cost and risk in the systems domain
SubOA: Operational analysis module	
SubOAOdB	Object editor for Play-Cards, concepts & systems/equipment etc.
SubOAScen	Scenario editor for scenarios and missions
SubOASim	Simulation engine and operational analysis module
SubOARes	Presentation of results, DE, ME, CE and System effect and capability tool
SubSA: Systems analysis and evaluation module	
SubSA	Systems analysis, evaluation and presentation model
SubRep	Document and report repository

4. Frame of reference

Design theory is a multi-disciplinary activity which solves open problems unlike basic ship theory that calculates, for example, a ship's speed. Ship design theory, on the other hand, ensures that the ship reaches the right speed for the right reason. But the significant component in design is that the ship is regarded as a complete system of systems in which all parts are linked and depend on each other in order to give maximum system effect for a valid and balanced size definition at the lowest cost, i.e. a design description, a feasible design concept.

Classical ship design procedures were largely unchanged during the first half of the 20th century. The complexity of large surface ships and submarine systems such as the SSBN and Polaris programmes stimulated the search for new approaches to design. Smaller conventional submarine projects were based on requirements, and the submarine design was redrawn and recalculated until the necessary balances for the submarine were achieved. New ideas were implemented in stages and to move forward in the development process, the design was "frozen" at different stages (vertical dotted lines in Figure 6) with the purpose to consolidate design choices and to reduce the uncertainties following the older Swedish design procedure. Unfortunately this had the side effect that creativity and alternative routes were limited early in the project. With long development times this often resulted in defence systems that were old already at the time of delivery, Nordin (2009). The vertical axis in Figure 6 represents the span of requirements and ambition.

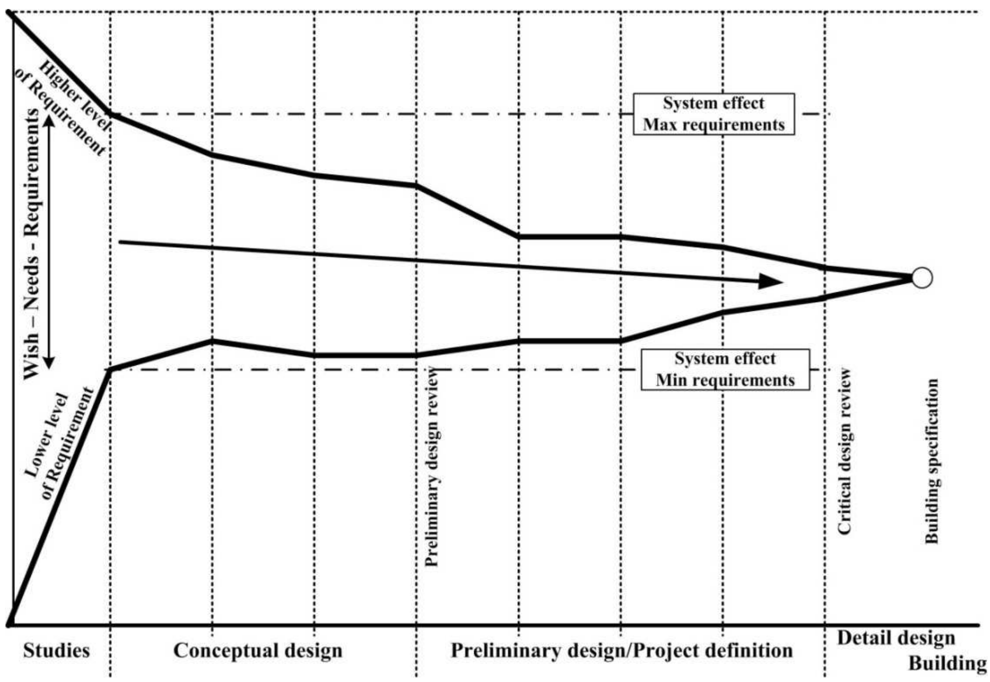

Figure 6: A view of classical convergence in design development, from needs to a complete building specification, see Paper E.

The purpose of the ship design process is to develop a valid design description of a feasible ship, at a level sufficient for its production, where its properties correspond to an expected behaviour in one or more specified operating conditions as defined by the customer and stakeholders. A design description, a concept, contains information about size, arrangement, cost and performance of the ship, its systems and components. As such, concepts are a way to express how and to what degree the specified functions are addressed at an early stage. The relevant performance is dependent on what roles and tasks the ship shall solve, a statement that was given early by af Chapman (1775), one of the earliest ship designers to base his work on a scientific foundation.

Several attempts have been made to describe the complex process of designing ships. One attempt was the initially popular design spiral by Evans (1959), which described the design as an iterative procedure with a progressively increased accuracy. Each turn in the spiral represents a complete review of the current level of detail for the whole concept. The centre symbolises that a balanced solution has been reached. During the same time computers were introduced in ship design to speed up calculations. The cost aspect of the project was introduced by Buxton (1972) and was introduced in the spiral after the technical design. Time was also added as a third dimension in the form of a helical corkscrew, see Andrews (1981). A design spiral including fundamental balances adapted for submarines was introduced by Nordin (1990), Figure 7, and complemented with system effect and signatures by Nordin (2009) to point out their significance for design. Provided that the options really existed, each round, in lack of integrated computer tools, took weeks to months of complex and expensive calculations to perform. Each treated option was still based on known solutions because the search for new knowledge through the development of new solutions would be too costly and time-consuming even if radically new designs did appear from time to time.

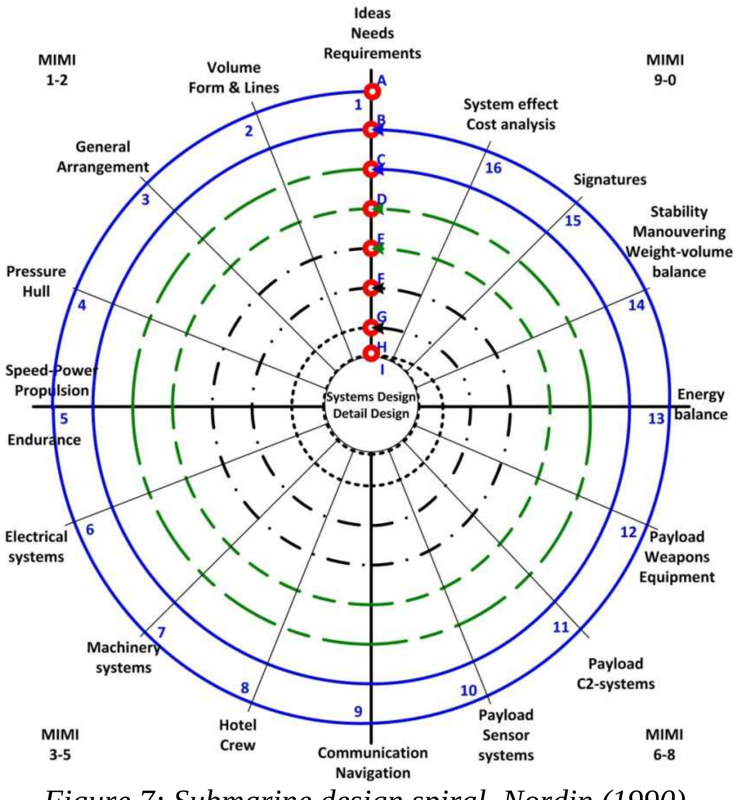

Figure 7: Submarine design spiral, Nordin (1990), and modified for system effect and signatures, Nordin (2009).

However, the design spiral did not solve the problem of describing the situation at a given time and thereby how to avoid embarking on less fortunate paths for design efforts during the early stages. These problems initiated new attempts to describe and develop the design process. Such concurrent engineering and decision-based design theories were described by Mistree et al. (1990), but missed the important factor that naval ships and submarines are physically & large and complex systems. This is however well documented and explained by Andrews (1986, 1998, 2011b & 2012), Van Griethuysen (2000), and Nowacki (2010). Particularly by Andrews (2011a & 2013) regarding elucidation of requirements.

The number of combinations of various system solutions has since been multiplied. Different design problems that earlier could seem relatively simple however complex, are today more multifaceted and even more complex. This complex cross-disciplined nature of a design problem means that a direct solution is not possible and prevents a direct design approach for the development of a design description to a level of detail useful as the basis for the concept specification of a submarine. The iterative procedure has since been established as the only feasible way ahead.

Technical design

Since the beginning of the 1990s, several developments have stimulated design based on naval architectural principals and systems theory for a holistic approach, where not only technical design is treated but also cost and operational aspects are included. From the early 2000s, with the development of computer technology and the matureness of model based systems engineering (MBSE) within systems analysis (SA), a more complete treatment of a cohesive and coherent design method has emerged as a strong tool in search of a best design when major factors of influence are included. This has further strengthened the naval architectural system approach. Some examples of models for submarine design are presented in Table 2 below.

Table 2: Example of models for submarine design.

Program name	Source	Year of introduction	Country/affiliation(s)
TC 117A	Wahlbom M	1973	Sweden/Kockums
“Parametric”	Jackson H	1986	US/MIT
SubDes	Nordin M	1990	Sweden/FMV/Chalmers
Neptune	Gössmann H	1991	Germany/IKL/HDW
SSCON	Burcher & Rydill	1994	UK/UCL/MOD
SUBCON	Andrews D	1996	UK MOD/UCL
SUBCEM	Van der Nat C	1999	NL/TuDelft/Nevesbu/RDM
“Russian model”	Kormilitsin & Khalizev	2001	Russia/Rubin/SMTU
ASSET	Brown A	2003	US/NSWC Carderock
SubParm	Nordin M	2009	Sweden/FMV/FOI/Chalmers
IPSM	Rodgers et al.	2010	Australia/DSTO

There also exists a submarine design model at MIT for civilian submersibles according to Allmendinger et al. (1990) and a second one according to Psallidas, Whitcomb and Hootman (2010a & b), i.e. based on the MIT Math model for surface ships that is used for education and design studies according to Whitcomb and Szatkowski, but following the principles of *SSCON* from UCL (Burcher & Rydill, 1994). Several companies such as Swedish SAAB Kockums, former Kockums AB, and BMT UK use the Paramarine program suite including the UCL Design Building Block (DBB) approach in their indigenous models. According to Van der Nat (1999), form and components' data are required to describe a submarine's performance. This information can be divided into three types; numerical, geometric and topological depending on which type of information they carry. Models with only numeric information have normally a higher uncertainty than models with both geometric and topological description according to Van der Nat (1999). The exemplified third model by Nordin (1990), the SubDes model, and the seventh model by Van der Nat (1999), the *SUBCEM* model, is based on numerical, geometric and topological information. The SubDes and the *SUBCEM* models are used in the system and installation domains for concept design. Design models in the systems and installations domains need a lot of information depending on the level of detailed description of design components, as discussed in Paper B.

For the earliest part of the conceptual design phase and the preliminary design phase there are modern models available based on Design Components represented by bounding boxes, functional volumes and building blocks in 2.5D or 3D. A common feature is that the design object, i.e. the submarine, is described with its shape using a parametric model, while tanks and components are described as blocks ranging from simple to more complex building blocks, i.e. functional volumes, with detailed components, units and systems. Nordin (1990) describes briefly such a model, *SubDes*, inspired by Andrews (1986). This is a 2.5-3D description for exploitation of the earliest part of the conceptual design phase including sizing and balancing. Later that approach was described in more detail by Andrews et al. (1996) in the model *SUBCON*, which is a 3D model for use in the earliest part of the concept design phase. Both these two models can be used from the very start of a project in the functional domain as well as in the system and installation domains.

A common factor in these three models (SubDes, SUBCON and SUBCEM) is that each Design Component, in addition to volume and shape information, are bearers of parametric information and properties such as weight, power and energy needs, generation or transformation, physical restrictions, materials or any other relevant attribute that might be needed to describe the actual component with its features. Design Components can be modelled with explicit data known from existing or historical designs in the system and installation domains. Design Components can also be modelled in a more generalised form in the functional domain. This is done through parametric expressions and relations where properties such as size, weight, etc. are carefully deduced from normalised data derived from existing or historical designs in the system and installation domains. Such Design Components can also be named generic building blocks in the functional domain according to Andrews (1996 & 2003b). According to Andrews (1996) it is also possible to start at a higher abstraction level and then gradually refine the content of the building blocks all the way to physical components. Nordin (2009) claims it is not only possible but also necessary to do so, in order to achieve a seamless transition between the needs domain and the three design domains i.e. the equivalence between functional, system and installation volumes.

Cost calculations

Cost estimates are of fundamental value well before design development and procurement have begun. Cost constraints and subsequent budgets usually do not come from technical design but most often arise as a maximum cost target, expressed in unit cost for a certain number of units, procurement cost, life-cycle cost and total ownership cost. These cost-targets are preferably set, usually by an administration, before a full project starts, i.e. after the conceptual phase. However, to get acceptance by an administration to start a new submarine project, a good cost estimate is needed already during the study and conceptual phases. Cost estimates therefore need to be as accurate as possible even though all requirements or even needs have not yet been established. The maritime industry and naval governmental agencies have a long tradition of estimating and calculating cost for various types of ships and submarines, including different business models, according to Nordin (2009). The basic model for estimating costs was already developed and in place for naval and merchant ship building before the Great War and systematically presented by Kari (1927-1948) for the merchant marine and later following the principles of a development in engineering economy by DeGarmo et al. (1942-1990). These basic models have been used and developed by the shipping industry (Stopford 1997) for estimating the total cost for different naval aspects of establishing and keeping the concept of Seapower (Pugh 1986). There are differences between military and commercial shipbuilding, as described by Birkler et al. (2005). Due to standardisation within merchant ship design as opposed to the on-going process of analysis and development for military systems provided by a few contractors (Arena et al. 2006) which are more expensive. The estimate of a future ship system's cost and the estimate of new subsystems' cost already in the early phases of a project in the functional as well as in the systems domain was introduced by Nordin (2009) and presented in more detail by Nordin & Garmelius (2015c).

Operational analysis, Systems engineering and Systems analysis

It is generally accepted that OA was introduced by the British government and its armed forces during the Second World War, especially as a mean to win the Battle of the Atlantic against the German submarines and their Wolfpacks, as reported by Morse & Kimball (1951) and Waddington (1973). In those days it was called Operational Research (OR) due to its nature of applying scientific methods in collecting and processing data from the field and in the search for best solutions to different military operational problems, e.g. anti-submarine problems related to the tactical and operational use of weapons and equipment. After the war, OR became an established method in not only military procurement and design but also as an integrated part of industrial management according to Churchman et al. (1957), Ackoff (1971) and Miser & Quade (1985). After the Second World War a sharp focus was directed towards various model types:

- Manual games theory.
- Analytical models (deterministic models).
- Monte Carlo models (random models).
- Combined analytical and Monte Carlo models (simulation).

During the 1980s, when graphics software matured, complete simulations could be implemented so that random event-driven processes and activities could be used. This enabled the development of analytical and Monte Carlo-based models with graphical interfaces. Game theory now made its entry into computer-based simulations. Game referees were replaced by an embodied simulation engine, within which all rules were computerised. However, OA was not generally integrated in the design process according to Nordin (1990) and Frits et al. (2002) and therefore both advocate a shift of design philosophies to incorporate operational effectiveness as part of the design process. Thus, the linkages between design variables (DV), weapons performance and tactics can be more thoroughly understood, and a vehicle with the greatest overall effectiveness can be created according to Frits et al. (2002). Following Hootman & Whitcomb (2005), such concurrent development of effectiveness models and engineering analysis is required to optimise a system and provide decision-makers with pertinent information to facilitate better informed requirements derivation. Based on the experience gained, so far not well documented in open literature, comprehensive OA models for evaluating designs were developed. This was done using a Systems Engineering approach with focus on stakeholders' requirements and validation. The general requirements identified from the study of the OA models, Nordin (2009), are that new OA models should be:

- Descriptive.
- Explanatory.
- Explorative.
- Integrated.
- Flexible.
- Adaptable.

The study by Nordin (2009) has directly highlighted the need for a type of OA model, which is integrated with the design and design teams activities, and that have the following characteristics:

- Generic structure of missions, scenarios and technical systems.
- Flexible so that both long simulations of complete missions as well as short simulations with intense duels can be performed.
- Adaptable to changes in the course of the analysis, e.g. adding new mission types and associated measures of effectiveness.
- Introduction of dynamic tactics and combat procedures, and event-driven dynamic scenarios and missions.
- Physical description of the 3D operational environment.
- Parametric descriptions of technical systems.
- Traceability between outcomes (results) and technical solution/system/function.
- Descriptions of human influence on the technical systems' outcomes.
- Ability to lock parameters so that more strict, clear and reduced simulations can be carried out, especially with regard to progressive verification and validation.
- Use of a graphical user interface (GUI).

It is hard to find anything in the open literature about military OA models, especially about submarine warfare. However, bits and pieces can be found after the Second World War, e.g. Morse and Kimball (1951), Kuenne (1965), Gripstad (1969), Zehna (1971), Waddington (1973), Wagner et al. (1999), Hootman & Whitcomb (2005) and Nordin (1990 & 2009). For more straightforward performance prediction of submarines, the following sources were found: Allmendinger (ed. 1999), Van der Nat (1999) and Kormilitsin & Khalizev (2001).

Today many scientists, engineers, and economists use classic elements of OA in contemporary computer based analysis and simulation models. Since the introduction of computer based models with high resolution graphics a wider array of requirements has emerged, where results are presented in a communicative form. The model is not aiming at final results only. It should also give the analyst an opportunity to explore different aspects of the problem. To do this the model must be descriptive and explanatory and also flexible and adaptable to relevant areas of interest, as pointed out by Nordin (2009) and in Paper C.

Traditionally, naval systems requirements have had a tendency to be shrouded with rigidity. Cementing the requirements on a design before a proper concept study has shown that a balanced design for the given needs exists is a direct obstruction of modern naval design principles. When it happens in the design of physically large naval integrated complex systems such as surface combatants and submarines, it is extremely costly. This subject was discussed by Andrews (2003a & 2013), Nordin (1990 & 2009) and in Paper A.

In the SE process issued by Department of Defence (DoD), USA, Figure 8 below, it is clear that the process is iterative and that the design synthesis in itself can influence deduced and developed requirements. However, allocation of requirements can only be set as a result of a Design synthesis in the early phases. Requirements are designed through the iterative design loop with the help of the Design synthesis. According to Andrews (2003a & 2011a), this elucidation of requirements, or clarification of the real needs following Nordin (2009 & Paper A), i.e. why the system is needed, is of vital importance for the design team during their concept design work in order to achieve a set of balanced requirements.

The MBSE approach advocates according to Rodgers et al. (2012) the use of dynamic system models that evolve in accuracy and fidelity through the project phases, and encourage the use of electronic media and tools. MBSE and ISO/IEC 15288 constitute the conditions for development of a coherent method in this thesis. The process focuses on the systematic traceability of an iterative design process, illustrated in Figure 8. However requirement allocation can only be performed after the result of a Design synthesis.

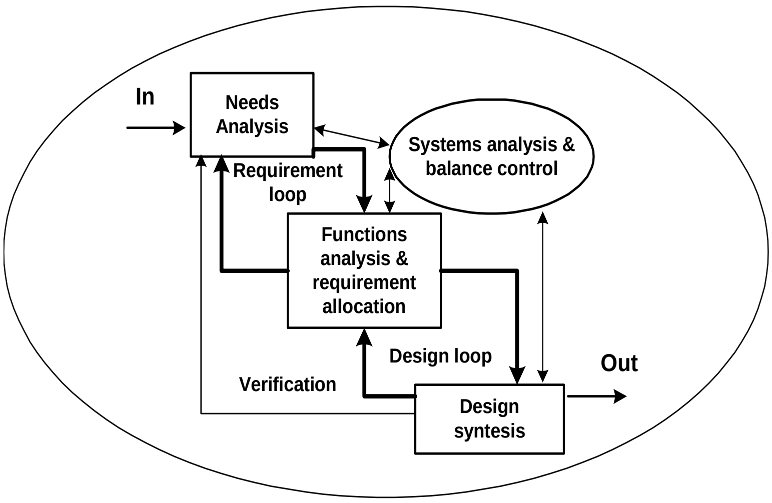

Figure 8: The iterative SE-process for each systems level according to DoD, USA, (2001).

The Systems Engineering approach is an interdisciplinary field of processes and methods with the purpose of providing a holistic view, i.e. not very different compared to Naval architecture. The development of Systems Engineering has however added some complementary value for Naval Integrated Complex Systems as presented earlier by Van Griethuysen (2000).

Ship design optimisation problems have ancient roots and offer cumbersome mathematical solutions. According to Brown and Salcedo (2003), the design space for ship design is non-linear, discontinuous and associated with a wide variety of conditions and thresholds.

During the 1990s several attempts were made to mathematically define the shape and arrangement of container ships, see e.g. Ray & Sha (1994) and Ray, Gokarn & Sha (1995), and to implement global optimisation methods based on a multi-criteria formulation for some objective functions, i.e. cost and performance. The idea was to have the ability to go from a representation of the design problem in the performance room to a best solution in the design room. This would indeed provide a very powerful tool according to Erikstad (2003). However, the author also states that this solution model is dependent on well-defined problems and objective functions, which can be described using continuous functions with *a* *priori* known conditions. This is seldom the case and especially not for NICS. Another problem with multi-criteria optimisation is that the solution might change dramatically, even at marginal variations of the relevant criteria. The combination of loosely set criteria and their oscillations in the design space gives low precision and confidence. A further problem, specific to naval ships, is that it is not their performances such as speed, endurance and payload that constitute the systems effectiveness, but rather the combined effect of them, see Paper C.

Critical naval ship objective attributes are mission effectiveness, cost and risk, according to Brown & Thomas (1998) and Brown & Salcedo (2003). These attributes must be presented individually, but simultaneously, in a manageable format for trade-off and decision-making.

Mission effectiveness or Measure of Effectiveness (MoE) for a certain mission is the combined effect of a set of Measure of Performances (MoP) according to Nordin (1990 & 2009) and Brown & Thomas (1998). Therefore MoPs define the performances of a ship system independent of mission scenarios. Design parameters (DPs) provide the physical description of the ship systems and therefore, DPs determine MoPs, and MoPs determine MoEs for different missions as presented in Paper C.

In Brown & Salcedo (2003), an optimisation method is presented that includes three components:

- An efficient and effective search of design space for non-dominated designs.
- Well-defined and quantitative measures of objective attributes.
- An effective format to describe the design space and to present non-dominated concepts for rational selection by the customer.

A multiple-objective genetic optimisation (MOGO) is used to search the design parameter space and identify non-dominated design concepts based on life-cycle cost and mission effectiveness. A Pareto frontier and selected generations of feasible designs are used to present results to the customer for selection of preferred alternatives.

The method is based on a subjective, i.e. expert opinion and pairwise comparison, Overall Measure of Effectiveness (OMoE) approach instead of a dynamic OA model, which in this combination with a genetic algorithm would result in a time-wise cumbersome or impossibly long calculation time according to Brown & Salcedo (2003). This approach might introduce in itself a risk of unbalanced and biased solutions.

The above presented method has been further developed and used as reported in Demko (2005), Good & Brown (2006) and Good (2006). A further development was the Operational Effectiveness Model (OEM) presented in Kerns (2011) and by Kerns, Brown and Woodward (2011). This was a compromise between the complex war-gaming models and expert opinion based OMoE models.

According to Kerns (2011) a rational and thorough effectiveness model would incorporate a computer war-gaming scenario that includes not only the ship design capabilities and threat capabilities but also accurately captures complex human and physical environment interactions based on a considerable number of variables and conditions. Such a war-gaming scenario would require a complex program or code that would be inefficient in the synthesis model.

Submarine operations

Today more than 90% of international trade is transported on ships through the major waterways, or in military terms Sea-Lines of Communications (SLOC), between the major populations centres of which 70% are located along the coast-line. According to Mahan (1890) naval power is crucial to secure these waterways and shipping lanes. Also, Corbett (1911), Gray & Barnett (1989), and Till (2004), support this principle.

In modern times not only ships use the sea. Energy supply and data communications are dependent on cables laid on the ocean floor. The major part of all electronically based financial transactions goes through these data lines along the seabed according to Lacroix et al. (2001). The concept of SLOC has therefore received more attention from a security point of view. According to Padfield (1999, 2005 & 2009) the development and prosperity of the West have been and are dependent on the security of this SLOC, i.e. this is a matter of strategic concern. The covert operation beneath the ocean surface may qualify as the submarine's most characteristic feature, along with its ability to act in a surprising and asymmetric way. These capabilities were the original drivers for the creation and development of submarines.

The ability to operate covertly against the shipping lane focal points, choke points, harbours and bases, including the capability to penetrate harbours and base areas, was developed from the very beginning. From these early tasks the submarines developed the ability to operate anywhere in the ocean against the sea lines of communications and points of interest during peace time as well as in war. The capability of naval forces to direct action and effect in different arenas can be described using the basic operational capabilities; command, intelligence, effect, mobility, protection and endurance. From a classical naval perspective according to Nordin (2009), these operational capabilities are divided into military operations, support operations and humanitarian operations:

- Sea Control.
    - Securing Command
    - Exercising Command
    - Disputing Command or Sea Denial
- Maritime Peace Support Operations.
    - Peace Keeping Operations
    - Peace Enforcement Operations
    - Peace Making Operations
    - Peace Building Operations
- Operations other than war.
    - Humanitarian Support Operations
    - Civil-Military Cooperation Operations.

The basis for all operational planning is the manoeuvre philosophy. In the multidimensional combat space this means to discover the opponent's critical weaknesses and subjecting them to a rapid and effective intervention, directly or indirectly. Precision operation in this respect is the core and extended driver of military technological development. The logic behind the manoeuvre philosophy is based on the main principle that one should never attack an enemy frontally. The tactic is to find an alternative path or position for reaching the goal from a more asymmetrical perspective. Exposed weaknesses in the opponent structure are explored and are thereafter used progressively to achieve a system breakdown of the opponent.

This makes the manoeuvre philosophy a more cost-efficient alternative to attrition warfare. The ultimate aim is to decrease the opponent's desire for continued warfare. Submarines have the ability to stay covert for a substantial time and by asymmetric behaviour early, forwardly and with surprise, carry out actions against an opponent with great effect. These actions may be direct or indirect and can be targeted directly against the opponent's vital points from where the opponent's centre of gravity can be reached or threatened.

Conventional submarines fulfil roles and solve different tasks during various tactical missions. One operation can include several mission types. An example of a representative number of tactical mission types is presented in Table 3, from Nordin (2009).

Table 3: Tactical mission types.

Tactical mission types	**NATO abbr.**
Surveillance & reconnaissance mission	SR
Intelligence & Surveillance mission	IS
Special Operations Warfare	SOW
Underwater Information Warfare	UIW
Underwater Work	UW
Mine Counter Warfare	MCW
Mine Warfare	MW
Anti-Submarine Warfare	ASW
Anti-Surface Warfare	ASuW
Anti-Ground Warfare	AGrW

The tactical mission types listed in Table 3 put different requirements on the submarine as a warship and especially on its combat systems (e.g. weapons, sensor and command systems). It is therefore important that any evaluation of the submarine operations must be able to single out the capabilities and effects for the different mission types, if one is to search for “best design” in the design space.

The effectiveness of the evaluation is dependent on the ability to trace the connection between tactical results, technical performance and cost from the system functions of the submarine. There are however different technical solutions for different submarine systems. These differences are linked to the choice of technical design for each submarine system and depend on a combination of the following:

- Submarine performance, such as underwater speed, endurance, signature etc.
- Submarine information handling; surveillance, communications, command and control systems.
- Submarine combat systems; weapons, ROV, UUV and divers etc.

A description of submarine operations must thus be capable of modelling the various tactical mission types and at the same time allow different combinations of the technical performance of various submarines and associated combat procedures. A tactical model must also be able to manage what a decision-making process and information model look like and how it commands and controls the general tactical decisions, as well as different decisions on combat procedures according to Paper C.

5. Method

Presentation of a general approach to design and validate a coherent design method that includes not only technical and cost information but also operational factors of influence.

5.1 A general approach to the research and development of design methods and models

As mentioned in chapter 3 the starting point for this research and development effort was an early observation within the Swedish defence industrial community that formed the origin for the problem definition. Initially an *ad hoc* procedure was used to search for information to define the problem base for a new method with slow progress as a result. The breakthrough came when simultaneously the search for the theoretical base was initiated and then consistently followed approach for applied research was used as described by Jörgensen (1992). This approach pays attention to the interplay between theory and practice as shown in Figure 9, below.

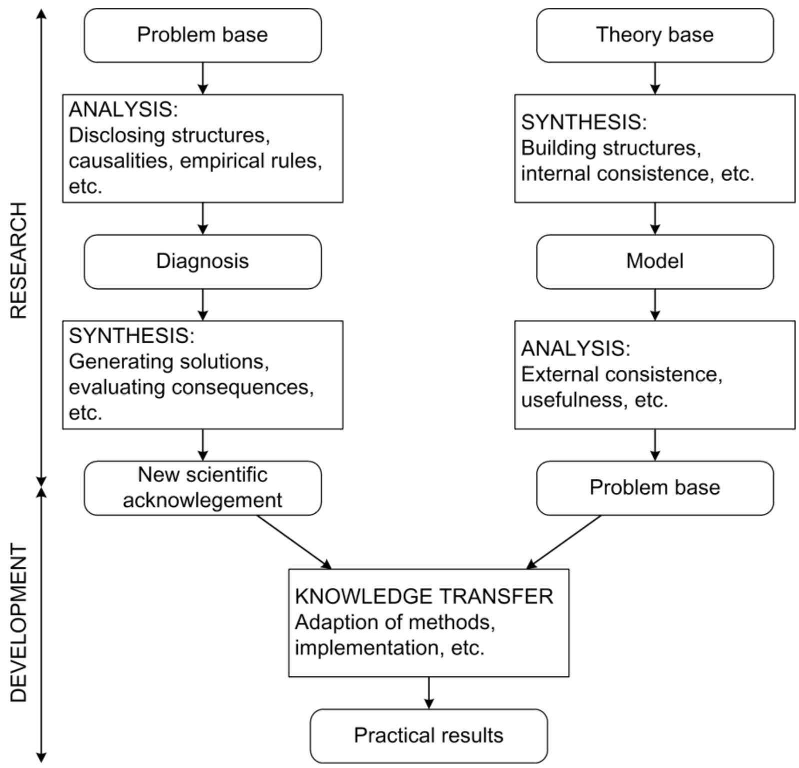

Figure 9: General approach for designing design models adapted from Jörgensen (1992).

This general approach focuses on the applicability of the method developed, where the solutions and hypotheses can be applied and checked against operational reality, i.e. examples and test cases of real submarine projects, educational projects and studies, redesigns and reengineered projects.

An earlier and more integrated use of design methods, previously applied only in later phases of the design process, is desirable, see Figure 10. This is made possible by introducing a Functional volume as a carrier of technical systems properties in an integrated design and calculation environment, based on technical, economical and operational factors of influence.

The origin of the method introduced here is the result of a general study of design by Nordin (1990) in particular the gap analysis of the existing design methods inspired the work. The original idea has been further elaborated (Nordin 2009 & Paper B). To achieve a steeper knowledge growth with higher precision early, with less time in the functions and systems domains during the study and conceptual design phases based on the introduction of a Functional volume, the following general approaches where applied. See Figure 10.

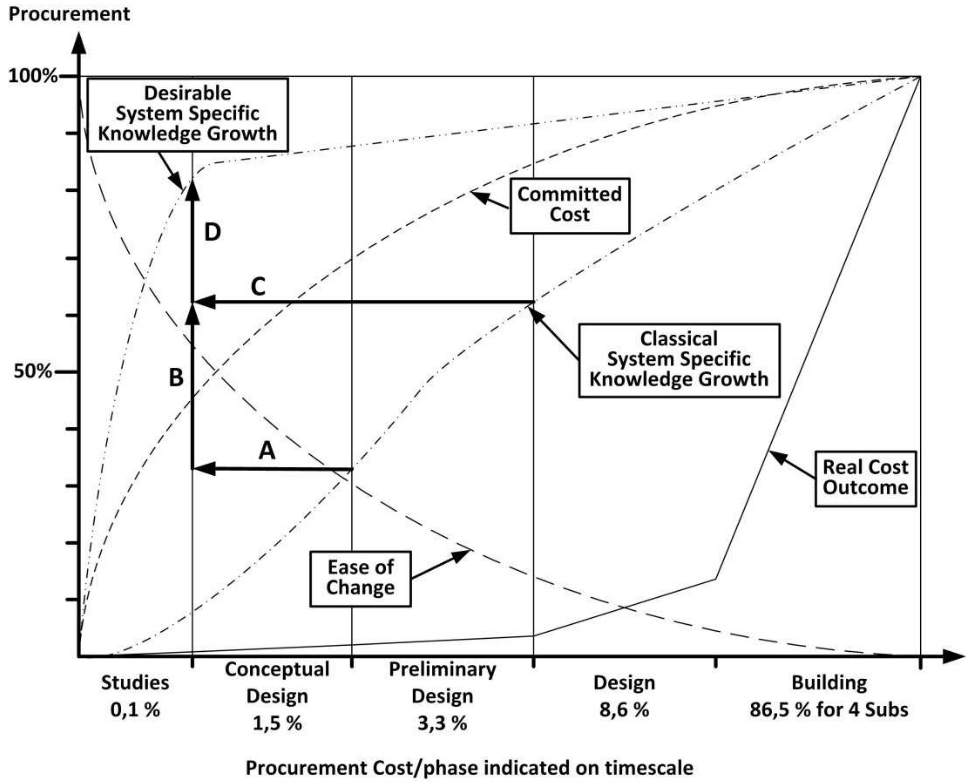

Figure 10: General approaches for achieving a steeper knowledge growth with higher precision in the functional domain.

The general approach is to integrate technical, economical and operational data in one coherent calculation environment and as a result of this enable the following steps:

Technical aspects on design:

A. Adding calculation methods, usually used during the conceptual design phase in the systems domain, to the functional domain, e.g. speed-power prediction and hydrostatic and stability calculations.
B. Integrating these methods in one tool, the SubParm model, will give better precision in the results.
C. By also adding calculation methods usually used in the systems and installation domains to the functional domain, e.g. pressure hull calculation and failure mode analysis for the hull.

D. Integrating all the methods in one tool, the SubParm model, with its capability to explore the design space will give higher precision for the Play-Cards and early and steeper knowledge growth in the functional domain.

Cost and system effect aspects on design:

A. Adding cost calculation methods, usually used during the conceptual design phase in the systems domain, to the functional domain.
B. Integrating cost methods in one tool, the SubParm model, will give more knowledge and better precision for the results.
C. Also adding system effect methods usually used during the conceptual and preliminary design phase in the systems and installation domains to the functional domain.
D. Integrating system effect results will give higher precision for the Play-Cards, and early and steeper knowledge growth in the functional domain

These steps were expected to generate steeper and higher knowledge growth. As a result it was expected that higher precision would be achieved with substantially shortened lead-times.

5.2 Validation of the design method

Validation of the result in designing design models and a method for this has been an on-going effort among researchers for years. According to Claesson (2006) the area of design methods in the field of engineering design is an area of engineering research that relies both on subjective statements and mathematical modelling, which make validation problematic. In Pedersen et al. (2000) an extensive framework for verification and validation is described i.e. *the validation square* in Figure 11.

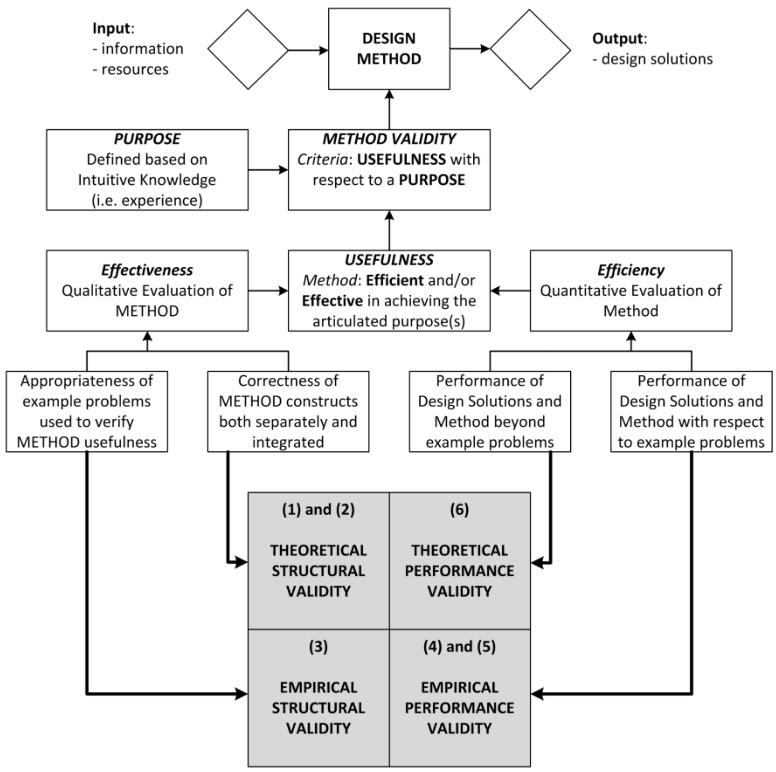

Figure 11: A general approach for validating design models, Pedersen et al. (2000).

This approach addresses the validation of internal consistency as well as of external relevance for some particular instance in order to build confidence in its general usefulness with respect to a purpose. Pedersen et al. (2000) associate the *usefulness* of a design method with whether the method provides design solutions ‘correctly’ (*effectiveness*) and whether it provides ‘correct’ design solutions (*efficiency*). Correctness in this context is design solutions with expectable operational performance (system effect) that are designed and realised with less cost and/or less time.

The validation square contains four validity constructs and is a combination of theoretical and empirical aspects with structural and performance aspects of the research results.

The four validity constructs, following Pedersen et al. (2000), are:

Theoretical structural validity:

1. Accepting the individual constructs constituting the method;
2. Accepting the internal consistency of the way the constructs are put together in the method;

Empirical structural validity:

3. Accepting the appropriateness of the example problems that will be used to verify the performance of the method;

Empirical performance validity:

4. Accepting that the outcome of the method is useful with respect to the initial purpose for some chosen example problem(s);
5. Accepting that the achieved usefulness is linked to applying the method;

Theoretical performance validity:

6. Accepting that the usefulness of the method is beyond the case studies.

Ultimately – faith in the method is accomplished.

The validation square framework is used during the validation process with the aim to evaluate and demonstrate the usefulness with respect to its purpose, i.e. the effectiveness and efficiency of the new coherent design method, based on qualitative and quantitative measures.

In the development process of this design method, the requirements on input data and algorithms were increased until the deviations were small. When deviations between the Play-Card and the real submarine were less than 5%, the models were considered successful.

Available information from historic submarines has been used for validation between Play-Cards with known submarine designs. The validation procedure includes four cases;

A. The accuracy of SubParm relative an existing design is shown in Paper B, Annex B: case A. Reengineering of Submarine type A17. This is reported in Nordin & Garmelius (2015a).
B. The ability of SubParm to conduct variations is shown in Paper B, Annex B: case B. Design of Submarine type Axx. This is reported in Nordin et al. (2015b).
C. The accuracy of a Play-Card in SubParm relative a more detailed concept design in SubDes, i.e. the seamlessness between domains is shown in Paper B, Annex B: case C. This is reported in Nordin et al. (2015b).
D. Redesign of Submarine type A17. It is shown that a better result can be achieved. This is reported in Nordin & Garmelius (2015b) and in Paper D and shown in Chapter 6.6.

6. Implementation of a coherent design method

Presentation of a coherent method for submarine design based on the results from the research and completed studies. Describes the different models in the coherent method based on the research questions and shows the coherent method's response to the model issues.

6.1 Description of a coherent design method for submarines

Design is an interdisciplinary process. When design methods are to be developed within a given domain, in this case, for a submarine system of systems, then operational knowledge and its technical architecture and dependencies up and down in the system chain, including its relations to cost and system effect, are key factors for a successful development.

Description of the submarine procurement process

The Swedish procurement management process, based on a tailored version of the Systems Engineering standard ISO/IEC 15288, was adapted to NICS during the development of the coherent design method for our submarines, see also Figure 1. In Figure 12, the V-model adapted for NICS is presented. It starts with user needs on the upper left and ends with a user validated system based on operational acceptance. Between the start and end-states, the V-model describes the left side as starting from a high system level with concept of operations, CONOPS, to a low system level based on decomposition and definition ending with the start of production. Successive higher levels, and then followed by subsystem integration and recomposition and testing, verification and validation until the complete system has been handed over to the user for operations.

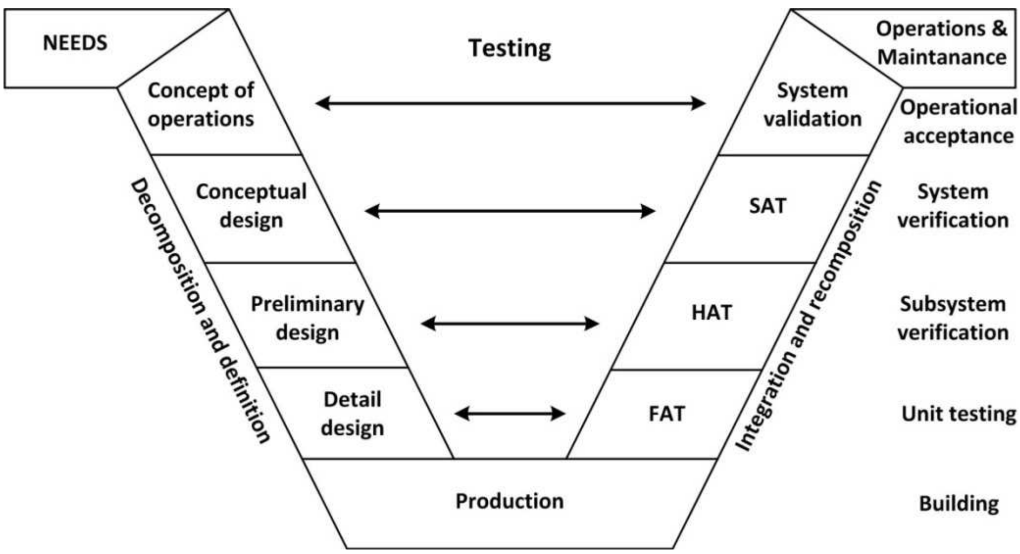

Figure 12: The SE V-model adapted for NICS design process.

This includes factory acceptance tests (FAT), harbour acceptance tests (HAT) and sea acceptance tests (SAT) where the technical systems are verified. The apparent indicated continuous process flow from left to right is in reality a highly iterative design process, as can be seen in Figure 13.

Generic description of the submarine design process
The submarine design process shown in Figure 13 was first introduced and tested during the submarine project Ub2000 by the author on the basis of experience gained from the earlier Swedish design process that was used in the submarine projects A11, A14, A17 and until the end of the preliminary design phase of project A19.

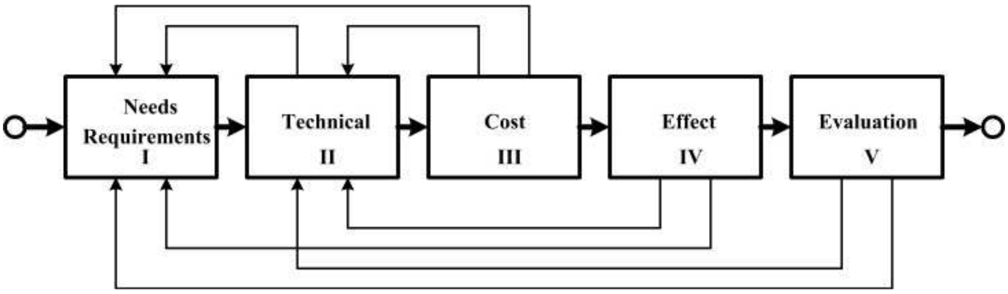

Figure 13: Flowchart of the submarine design process.

However, a relevant model based on the idea of the coherent design method approach with five (I-V) major parts was found missing or insufficient, these identified parts where:

I. A model for structuring and documentation of deduced needs and designed requirements with the help of model II-V.
II. A technical synthesised design model for fast parametric variation and exploration of the design space with the help of an initial concept, i.e. a Play-Card. A technical design synthesised design model for concept studies and design based on the Play-Cards' style, arrangement and generated budgets (weight, volume, performance and cost). Paper A.
III. A cost estimation model for Play-Cards and concepts, including a model for pre-project estimations based on historic data for size and number of units produced. Paper A.
IV. A system effect model for calculation of measure of effectiveness related to mission types of interest. Paper C.
V. A systems analysis model for evaluation of designed Play-Cards and concepts. Paper D.

This process, depicted in Figure 13, will be run through for each design domain. If any of the steps; technical design, cost prediction or effect calculation is not conclusive under the conditions that apply to the given set of needs, the process returns to previous steps until a consistent result is reached.

Early in the process of developing a coherent design method, it was foreseen that a key factor for success was that the major characteristics and performances for the design object, i.e. submarine Play-Card or concept, must be valid, equivalent and seamless, between domains and domain transitions. A schematic picture of domain transitions in the design process is sketched in Figure 14.

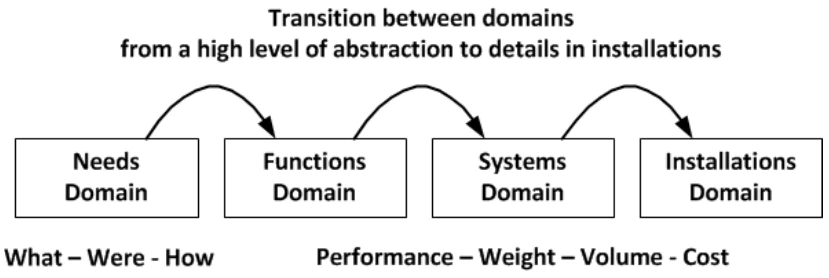

Figure 14: Schematic picture of domain transitions during the design process, from the needs domain to the three design domains.

The iterative approach of refining the design objects through gradual expansion and reduction through the use of controlled convergence, Pugh (1981), was developed to explore the design space, in search of a suitable design area(s)/point(s) in the design room. Generally the process moves from the design space to the design room and converges to a design area(s)/point(s) as illustrated by Figure 15 where several possible design points can exist.

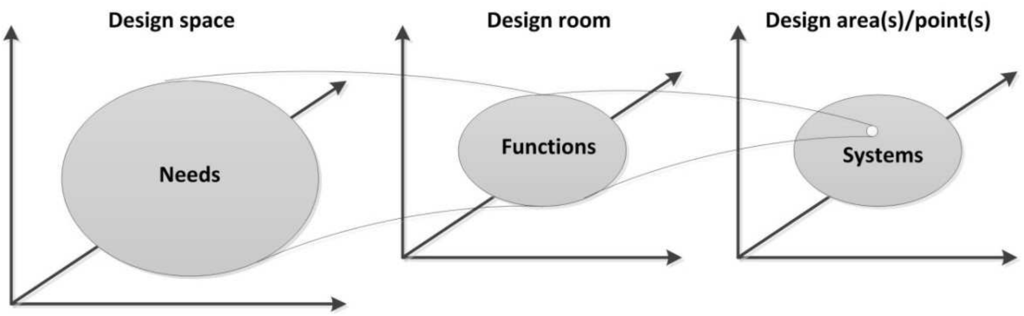

Figure 15: From the design space via the design room to a design area(s)/point(s).

Description of a coherent submarine design method

The coherent method is based on the five parts sketched in the submarine design process in Figure 13. These parts have been developed to models within the combined toolbox for Submarine analysis and design (SubAn). These models are, see also Figure 13:

- A model for identification of needs and deduction of initial operational and technical requirements. See section 6.2.
  Implemented in toolbox SubFunc.
- A model for the technical system design. See section 6.3.
  Implemented in two toolboxes SubParm and SubDes.
- A model of system cost prediction. See section 6.4.
  Implemented in toolboxes SubParm and SubCost.
- A model for system effect calculations. See section 6.5.
  Implemented in operational analysis toolbox SubOA.
- A model for evaluation and selection. See section 6.6.
  Implemented in systems analysis toolbox SubSA.

6.2 A model for identification of initial operational needs – mission analysis

Early in the development process it was clear that not only the customer, the user and the stakeholders but also the design team has to know the rationale behind stated needs – The Why. The development is dependent on a more general level of knowledge, from the strategic appreciation of the problem down to operational concepts, i.e. CONOPS, and individual mission statements, i.e. from relevant mission types, see Table 3, to related mission profiles – the initial set of operational needs, see Figure 16.

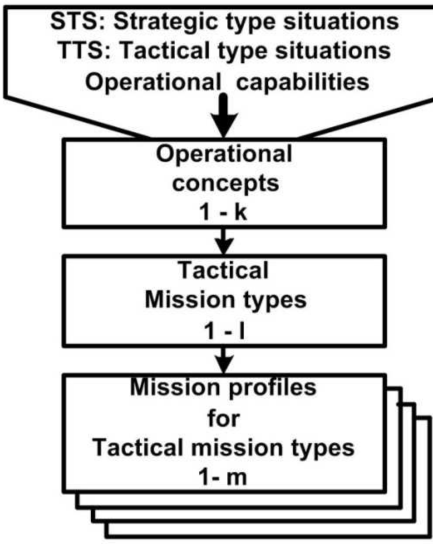

Figure 16: Development of needs from a strategic appreciation to operational concepts, tactical missions and mission profiles.

The initial set of operational needs is defined by CONOPS and What, Where and How statements:

- WHAT: What roles and tasks in the different mission types shall the system perform? This also includes type of payload, i.e. related to roles, tasks and missions.
- WHERE: Where shall the system operate, in which environment?
- HOW: How the tasks shall be solved. Expressed in CONOPS and mission profiles.

The mission analysis aim is to identify the needs and deduce relevant initial technical requirements based on the CONOPS and stated needs. A planned mission profile (1) is developed in a relevant area of operation. This mission profile is divided into phases (2) with planned general activities (PGA) (3) for the complete submarine and further subdivided into planned activities (PA) (4) executed by the submarine's subsystems and payload that sets the planned technical requirements on the submarine's system functions, as illustrated below in Figure 17.

From this planned mission profile a matrix from the start of phase A to the end of phase E is developed for the entire mission. This matrix provides a structure that then can be populated with planned requirements from other mission profiles of interest. Then, with the use of a design object that executes its mission profile and confronts its surrounding environment (scenario) the event based tactical requirements on the design object can be identified and deduced from the event-driven operational analysis simulation model SubOA with the help of the mission analysis model SubFunc. As a result from these events, new event-based tactical decisions are executed which generate a set of tactical general activities (TGA) for the submarine and which are further divided into tactical activities (TA) executed by the submarine's system functions and payload that sets the tactical technical requirements on the system functions.

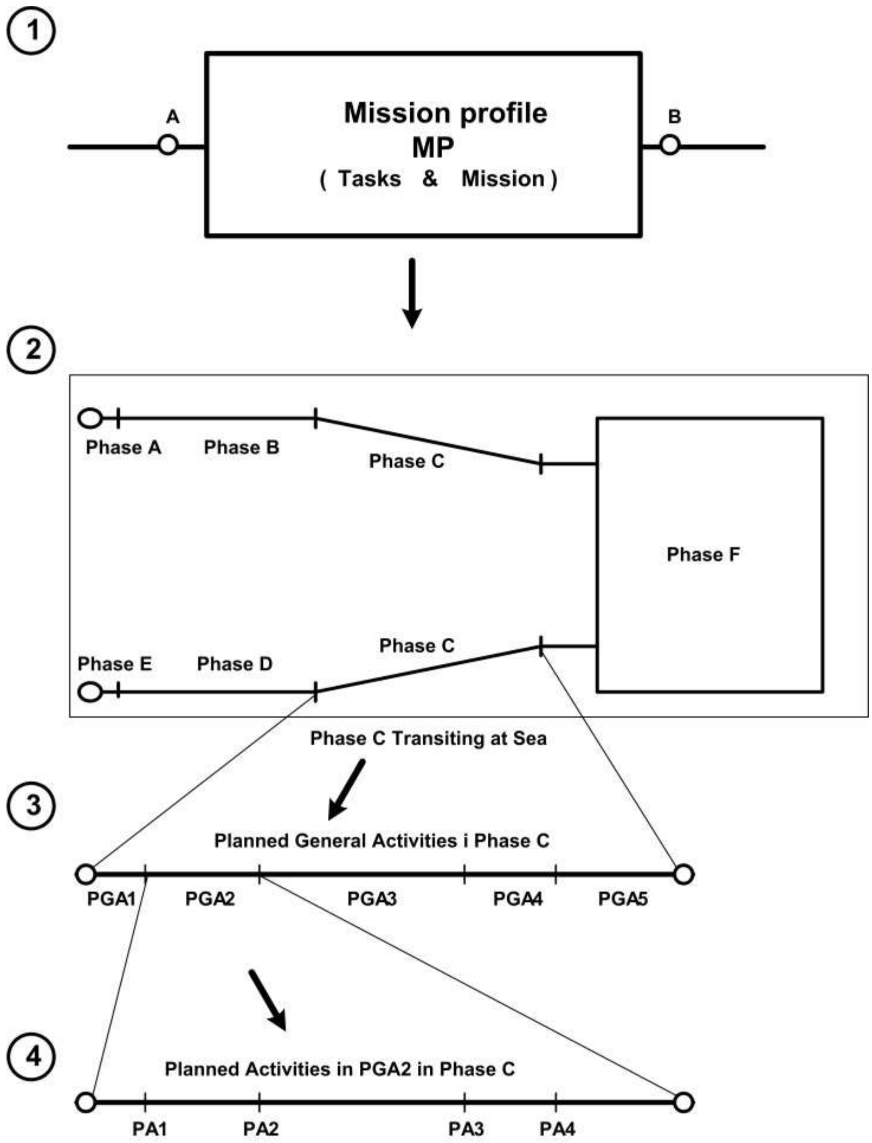

Figure 17: Decomposition of a planned operation profile via phases to planned general activities and activities.

As a result, both the planned and the event-based system functions and their initial requirements are compiled. Sensitivity analysis with the help of the generic submarine design model ensures that both the system functions and their requirements are valid for the current conditions. Systematic use of this procedure, i.e. with the use of a design object, for relevant and defining mission types and profiles, in geographical regions of interest, will help to identify the initial technical requirements during the mission analysis.

6.3 A model for technical system design

The submarine as a system of systems

In a modern defence system, a submarine is a component, a system in itself usually as a system of several systems in a navy. This hierarchy of systems follows a principal structure exemplified below:

Level 0: Ministry of defence and National defence.
Level 1: Navy, Army and Air Force etc.
Level 2: A Submarine system as a whole (several submarines including infrastructure, training, maintenance, documentation, services, etc.).
Level 3: A submarine as a whole, with several levels of subsystems.
Level 4: Submarine subsystems on level 4.
Level 5: Submarine sub-subsystems on level 5.
Level 6: Submarine sub-sub-subsystems on level 6 etc.

Initial operational needs and requirements are usually related to level 3 due to their direct relation to why submarines are needed in a defence structure. Whereas other needs, such as training, maintenance, documentation, services etc., not only cascade downwards in the level structure during design, but they are usually also related to higher levels, i.e. level 3 to level 1 due to their dependencies on infrastructure, bases, manning, training facilities, policies etc. These needs usually emerge as work progresses for the design team and during discussions with the customer and stakeholders.

Submarine system functions structure

A functional structure was initially deduced and developed during the Swedish submarine projects A11 Sjöormen and A14 Näcken. To this system functions structure has since then been added system functions for several modern submarines including both ADP and AIP submarines. This has refined the aggregated system functions structure following Nordin (2009), and is depicted in Table 4.

Table 4: The submarine system functions structure.

Submarine system functions structure	
System functions	Functional description of the aggregated system functions
1. Hull	To exclude water, sustain the pressure at depth, to embrace and carry the system functions, payload, and reduce the resistance of the hull form
2. Crew	To man the boat and host a crew
3. Protection	To operate covertly, detect weapons, counter manoeuvre, deploy counter measure and to sustain damage
4. Safety	To secure the survival and rescue of the crew
5. Energy	To generate, transform, store and distribute energy
6. Propulsion	To propel
7. Manoeuvring	To manoeuvre
8. Navigation	To navigate
9. Communication	To communicate
10. Surveillance	To survey acoustically, optically, electrically, magnetically etc.
11. Command & control	To command and control
12. Engagement	To engage directly or indirectly

This structure is intended to be used as a catalogue of submarine system functions for the benefit of the designer when the design of Play-Cards starts. This also includes the possibility to manually add innovative system functions for tests of new approaches and thus makes it possible to analyse the consequences when adding a “What if” system with its particulars.

Design of submarine concepts

One of the key issues for the coherent design method for submarines is how to create physically feasible and balanced representations of submarines in the early phases of design. Design is done in two steps:

1. To ensure an early and fast exploration of the design space with the aim to identify the appropriate design area(s)/point(s) for concept design, several initial concepts of different styles and performances, i.e. Play-Cards are designed in the Study phase, see Figures 18, 20 and 21, with the help of SubParm.
2. To further develop, refine and detail a number of selected concepts so that, after evaluation, one or two concepts can be chosen for preliminary design, see Figures 18 and 20, with the help of SubDes.

Consequently, the technical system design starts in the functions domain during the study phase and continues in the systems domain during the conceptual design phase. The workflow from mission analysis and initial requirements via Play-Card exploration and parametric studies to concept studies is illustrated in Figure 18 below.

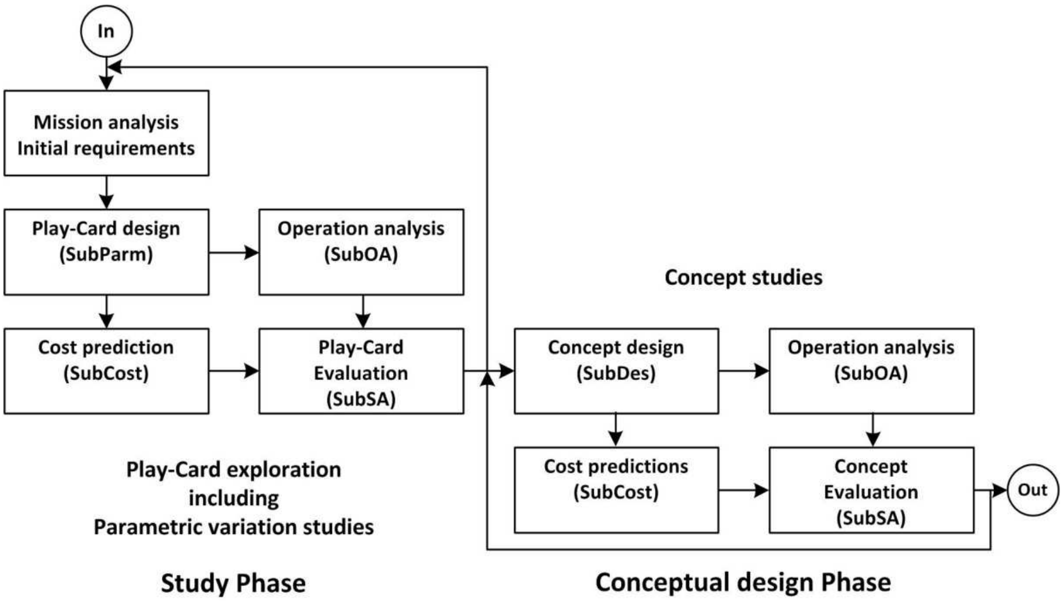

Figure 18: Flow chart of the study and conceptual design phases.

The identified system functions are packed into a consistent representation of the submarine. To manage the incremental rise of detailed content in the representations, from Play-Cards to the submarine product models, different levels of abstraction are used, i.e. a higher level of abstraction corresponds to a higher level of aggregation of components. This is illustrated below in Figure 19. In the functional domain only the initial concepts are described in the coherent method, see Paper B for details. In the initial concept model, the available volume (VR) for a chosen style shall be greater than the required functional volume (VF). This also includes margins. At the same time, the buoyancy (B) shall be equal to, and positioned over the mass (G) to secure balance. This includes that there shall be no resulting moment (M=0). The result is sized and balanced Play-Cards including budgets for volume, weight, performance and cost. These Play-Cards are exported to the concept design model, which is the next step. In the conceptual design phase, the designer continues to develop the concepts.

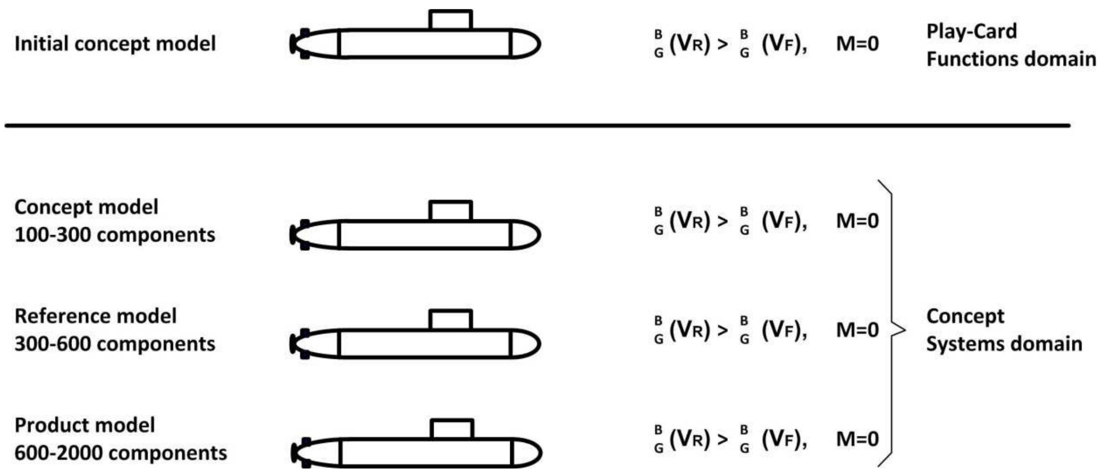

Figure 19: Different levels of abstraction during conceptual work.

In the conceptual design phase, the degree of abstraction is represented by the number of components. Figure 19 above indicates the level of detail by the number of components that the different models contain. The number of components is also an indicator for the time needed to develop, refine and optimise a concept.

Sizing and balancing of the submarine design object

The size prediction and balancing, see steps A and B in Figure 20, of an initial concept with its packed functional volumes representing budgets for further concept design are done in the functions domain based on an initial set of operational requirements. For an initial concept the technical design includes weight-volume and energy-power balances and related cost level. Balancing is an on-going activity in the systems domain where all design elements in a concept such as hull sections, tanks and installations with their components are designed and assigned. As a concept is designed, also the signature-vulnerability level is of interest. These balances and set levels govern the design of a submarine:

- Weight-volume balance. The available submarine volume is equal to or larger than the required functional volume, alternatively the systems and component volumes. The sum of all weights and margins, including different mission specific payloads and water densities, is equal to the current tonnage (displacement) so that the submarine neither sinks nor surfaces. The moment balance must be met in both surfaced and submerged conditions within the rules for static and dynamic stability and manoeuvrability.
- Energy-power balance. The sum of all the energies and power outputs of various kinds in the submarine meets the operational requirements.
- Signature-vulnerability level. To set up a signature profile that does not exceed the operational requirements on detection for the different signature fields in comparison to the design object's level of vulnerability to different weapon systems. This level also includes system effect studies and analysis.
- The technical system cost level. Ensure that the predicted cost is within budget.

The technical system design starts in the functions domain during the study phase and continues in the systems domain during the conceptual design phase. The workflow from initial operational requirements via parametric studies to concept studies is illustrated in Figure 20 below. As concepts evolve, and subsystems are refined and optimised, a higher level of detail is reached, see C in Figure 20. This is essentially the basic technical process for Play-Cards and concepts and shows the iterative approach.

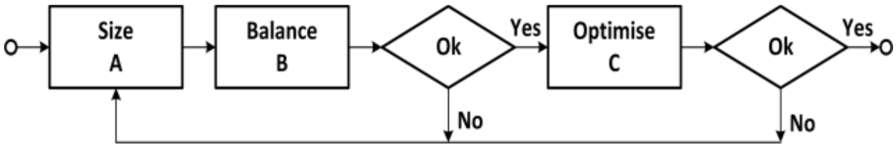

Figure 20: Technical system design.

The generic submarine design model for Play-Card design and parametric variation
The generic submarine design model, SubParm, is used to quickly generate design objects, i.e. Play-Cards, from initial operational and system function requirements.

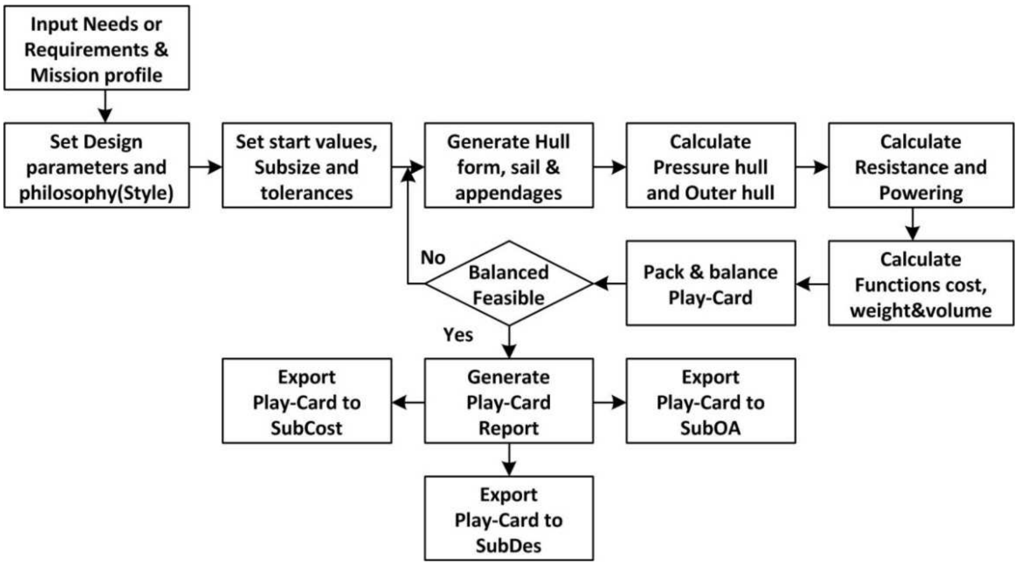

Figure 21: The generic submarine model – a synthesised model for Play-Card design, including parametric variation.

The generic submarine design model searches iteratively for the minimum size of a Play-Card that satisfies performance, power-energy, weight-volume and moment criteria. The multiple purposes of the parametric model are:

- To act as a stimulator in the mission analysis in combination with the operational analysis model.
- To explore the design space so that the design room can be adequately explored in such a way that the size of Play-Cards can be identified, see steps A and B in Figure 20, regarding technical system design.
- To vary the essential parameters in parametric and sensitivity analysis to gain a deeper understanding of the Play-Card's position in the design room.
- Play-Cards constitute the starting point with budgets (volume, weight, performance and Cost) and margins for concept studies and concept design.

The concept exploration model

In the concept design model, SubDes, the designer is given the freedom to design the concept in any desired way. An integrated calculation engine keeps track of all the data in the concept and supports this design freedom, including budgets given by a Play-Card, and as a result, the designer can concentrate on balancing the complete submarine and refine and optimise subsystems. See the design example in Figure 22, from Paper B and Nordin et al. (2015b). The system scripts manage the knowledge database in the concept model. A system script contains historical as well as system specific information for a given system including different options for design.

The multiple purposes of the conceptual design model are:

- To further refine, balance and optimise concepts within the identified design room as shown in steps B and C in Figure 20.
- To freely explore and generate alternative concepts in the design room.
- To reverse engineer existing submarines.

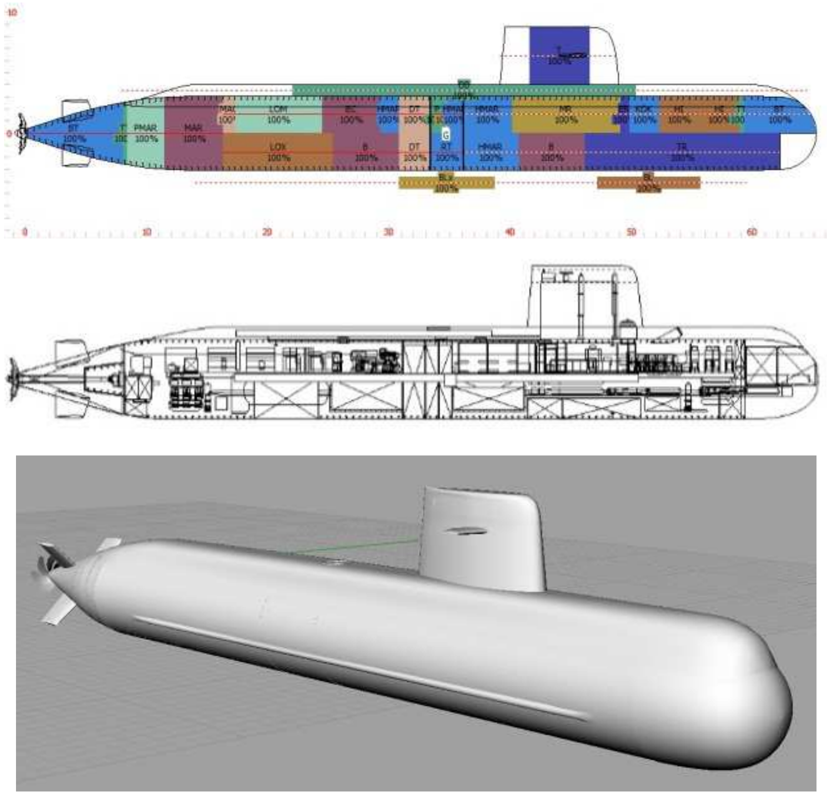

Figure 22: Technical system design: a Play-Card developed to a concept from top to bottom in initially a 2D view to a 3D view.

6.4 A model for system cost predictions and risk mitigation

The cost prediction is an essential part of the design process. The cost prediction model is not fully described in this thesis. A detailed description of this model is given in the report by Nordin & Garmelius (2015c). This model is based on developed normal costing procedures adapted for the early phases. However, a few features of the cost prediction method need to be communicated to understand the full influence of cost predictions in the early phases of design. Four cost methods are used in the model:

- Before a project has started as an initial cost budge.t
- In the functions domain when designing Play-Cards and calculating functional costs.
- In the systems domain when designing concepts and calculating system cost.
- In the installation domain, the model for the systems domain is used, but with higher. resolution, as an independent control procedure when the submarine concept matures to ready submarines at the yard.

Before a new submarine project is started, there is a need to have an appreciation of what a future acquisition may cost during development, procurement and operation, i.e. the Life-cycle cost (LCC) or Total ownership cost (TOC). To support this, statistics from historic and previous projects is used. Several factors influence the cost predictions at this stage, such as:

- Market price, cooperation or parent navy cost principles.
- Number of submarines to be built (Serial and learning effects).
- Number of yards where they are built (Restart of serial and learning curves).
- Size, complexity/integration of the built submarines.
- Ambition level on non-recurrent costs such as research & development and design.
- Operational patterns and maintenance procedures.

All initial concepts in terms of a Play-Card contain functional data. These script-based data are retrieved from the database containing current design components and historic statistics of the different functions' performance, cost, weight and volume etc. When a Play-Card is generated, the result is a design description with a predicted cost in the functions domain. A new project will normally also develop new functions and features. By using the Play-Cards with these new scripted functions in the functions domain, these added costs are predicted.

A concept contains system data. These system data are retrieved from the script-based database containing historical as well as up to date statistics of the various systems' performance, cost, weight and shape etc. The cost is calculated and assigned to the system groups containing engineering hours, workshop hours, purchased materials & supplies and services. The function and system cost tables are modified for the number of units to be acquired. The cost of alternative developments can be calculated and predicted by use of different indices and time periods for the various system groups. In this way the complete life-cycle cost is calculated and compiled for a complete submarine project.

Costs and budgets for Play-Cards and concepts can at any time be risk-analysed and a Measure of Risk (MoR) can be set with the Lichtenberg Delphi based risk mitigation procedure described in Nordin & Garmelius (2015c) and in detail in Lichtenberg (2000).

6.5 A model for system effectiveness calculations

One essential part of system design is the model for measurement and calculation of the system effectiveness or the Measure of Effectiveness, MoE, as presented in Paper C. Within the coherent design method, this is performed by SubOA using a simulation and event-driven Monte Carlo operational analysis model. In this model we can study a submarine's capacity to execute the planned missions in an environment that interacts with the submarine under a set of rules.

The submarine's performance and systems effectiveness are measured and calculated. The results are compared and evaluated against the results for other Play-Cards. The model consists of the following parts:

- A database of actors with their vehicles, equipment, sensor systems, tactics and weapons, as well as decision-making rules.
- A scenario editor for generating missions and scenarios.
- A simulation programme for operational analysis.
- Results and database management for the system effectiveness analysis.
- System effectiveness measurement and calculation including a report generator.
- A test system.

With an editor, a scenario can be designed for a given geographical area of operation. This area includes an environmental description, which will interact with the different sensor systems involved. The scenario editor is also used to generate the different mission profiles for the submarine. One run through the mission profile is called an elementary run or just a run.

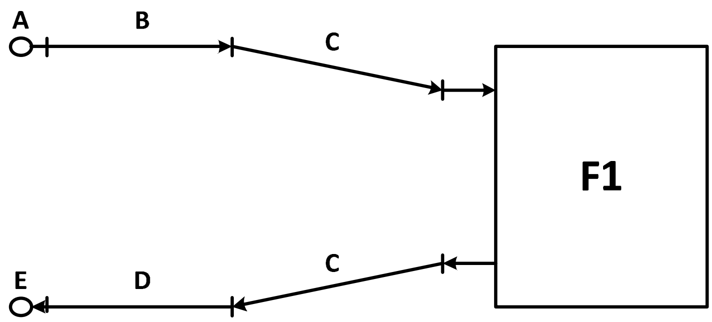

Figure 23: Sketch of a mission profile for SR missions with the phase sequence A-B-C-F1-C-D-E.

A mission profile for a Surveillance & Reconnaissance mission, SR mission (F1), is illustrated in Figure 23. The submarine starts its mission in a base (Phase type A) and sails out to the open sea (Phase type B). From there the submarine transits to the operational area (Phase type C). In the operations area the submarine begins the SR mission (Phase type F1, see Figure 24) for the duration of T hours (T_0 to T_1). After that, the submarine leaves for base and the sequence of phases is reversed until the submarine reaches its base (Phase type E).

During simulation, the submarine is going through the planned mission profile until there is a disturbance, a contact, detected by the submarine's sensors. The artificial commanding officer then, based on tactical rules, makes a tactical decision on how to act, i.e. combat procedures.

This will be an on-going process until there are no more disturbances, the submarine has been sunk or the submarine has returned to base. During simulation, the model measures and collects data for later calculation of MoE for the actual mission. Depending on complexity, a simulation can contain between 100 to 5000 runs until the MoE has converged.

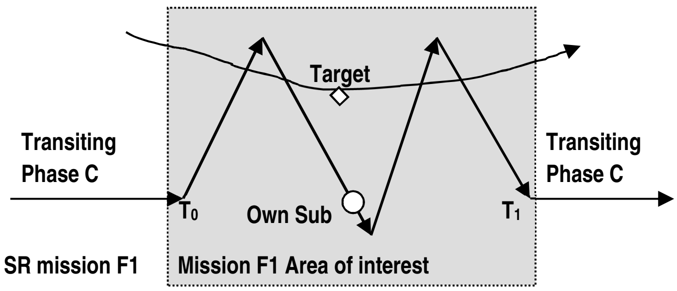

Figure 24: An example of an SR mission phase F1 including a submarine and one target of interest.

During the simulation, data elements (DE) from the initiation of the simulation, together with the measured data elements (ME), are stored in a database. After the simulations of several different missions and mission types under diverse conditions, the data are used for calculation of the overall MoE (OMoE) for each submarine. The result can vary between zero and one, see Figure 25 below.

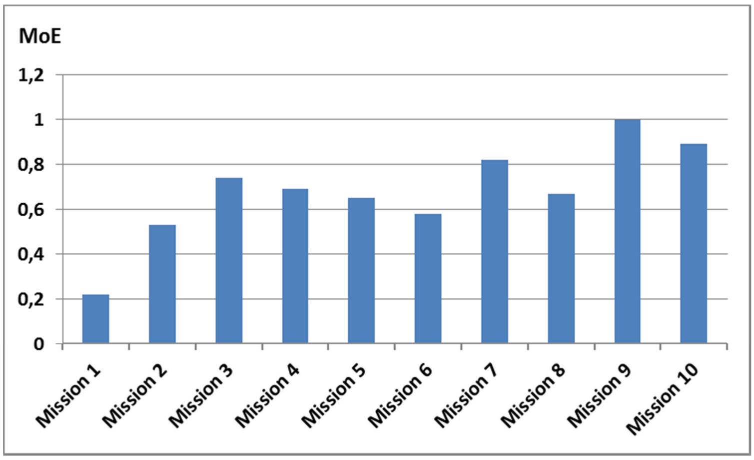

Figure 25: System effectiveness results for a submarine based on ten different SR missions in different environments.

Submarines operating in real situations encounter a unique mix of circumstances, which will form new understanding of the missions. The OA model must therefore be able to handle upcoming surprises from the submarine's adversaries in peacetime operations as well as war situations in a tactically correct way. It was therefore concluded that it is important that the tactical rules and combat procedures reflect these real situations and that the used set of rules is audited by experienced officers. Having done that, it was later shown that the model behaved according to the current appreciation of tactics. Tactics and combat procedures need to be constantly reviewed and updated to ensure a correct behaviour of the opposing forces.

6.6 A model for evaluation and selection in search of the best design

In support of the selection process, cost data and system effectiveness data for various simulated scenarios for the developed Play-Cards and/or concepts are compiled following Paper D. The traceability of both system cost and system effect back to the technical system description from the results of the simulations in the OA model allows various combinations of results to be compared and presented. Priorities between various types of missions can be reviewed and criteria can be adjusted.

An *a priori* preference vector between different mission types can be used but it is recommended that this is avoided until all quantitative results have been calculated and presented in an unbiased form. It is then possible to implement *a posteriori* preference vector from the decision-maker. Figure 26 illustrates the principle of a cost-effectiveness chart used in the evaluation and selection for NICS. The design room is bounded by two straight lines: the vertical line marks the maximum allowed cost for the acquisition and the horizontal line the minimum acceptable system effectiveness. This can be a specified reference system or stated requirement.

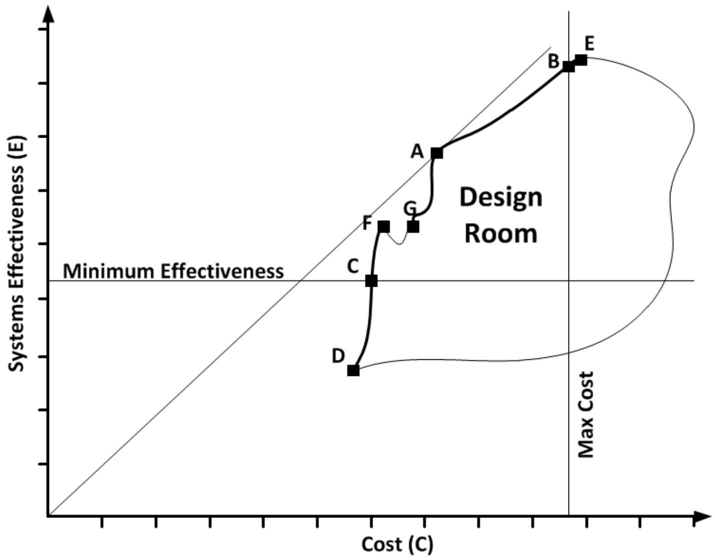

Figure 26: The design room with the different restrictions on minimum effectiveness and maximum cost and the highest quotient between effectiveness and cost.

In general the area to the right of the line restricted by the points C-F-G-A-B is of interest, and the point A is of special interest due to the highest quotient value between effectiveness and cost. The area or neighbouring solutions are usually of interest. So is the steep curve between points G and A, whereas the interest in curve A to B is depending on its slope, and can therefore be of greater or lesser importance. The point C is the cheapest acceptable solution whereas point B has the best effectiveness within the given cost limit. The two points F & G are low cost alternatives with equal acceptable effectiveness. Points outside the cost and effectiveness restrictions, including point D and E are of no interest. The thicker curve connecting points D-C-F and points G-A-B-E, represents the Pareto front of the best design solutions for this mission type. By populating Figure 26 from Paper D & E with points of cost and effectiveness corresponding to different Play-Cards or concepts we arrive at Figure 27 and 28, where it is possible to study the interesting features of a developed design room in a two dimensional objective attributes space. In an actual simulation, exemplified in Figure 27-29, from Paper D and reported in Nordin, Garmelius & Bossér (2015b), the Pareto front is point-based with denser and sparser packed points and with one or several areas of not so satisfactory solutions corresponding to the curve between points F and G in Figure 26.

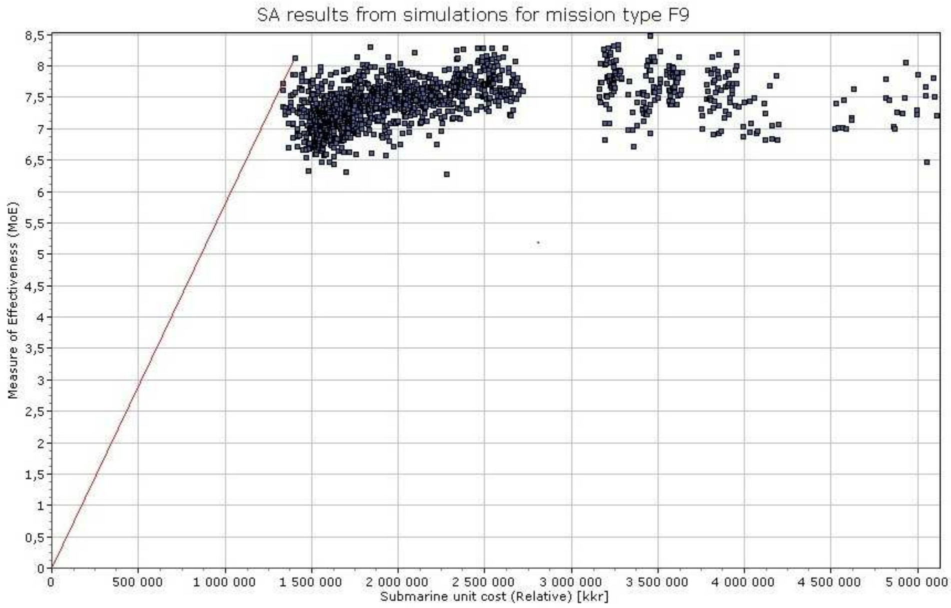

Figure 27: The design room from the results of the redesign of the submarine type A17 for one ASuW mission type.

We can get a better appreciation of the design room by studying a zoomed-in part of Figure 27, the result from the redesign of Swedish submarine project A17 conducting a ASuW mission against an invasion fleet. The results for this one mission type, system cost and system effectiveness, are marked in Figure 28, from Nordin, Garmelius & Bossér (2015b). The result shows an increase in Measure of effectiveness of up to 15% for this particular mission compared to the original old design.

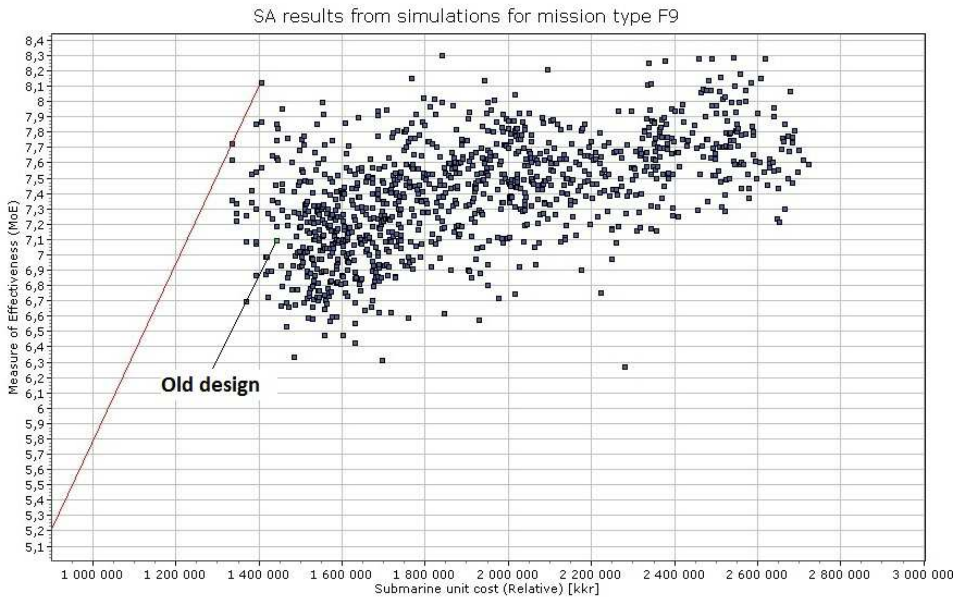

Figure 28: The zoomed-in design room from the results of the redesign of the submarine type A17 for one ASuW mission type.

In Figure 29 from Nordin, Garmelius & Bossér (2015b), the possible 51 design points are shown within the borders of minimum level of MoE (blue horizontal line), maximum level of cost (blue vertical line) and the Pareto front (green dashed line) for one mission type. The original old design point for A17 is given as reference. A17 was originally only evaluated for one mission type, namely an ASuW mission against an invasion fleet. This was at the time the predominant war scenario.

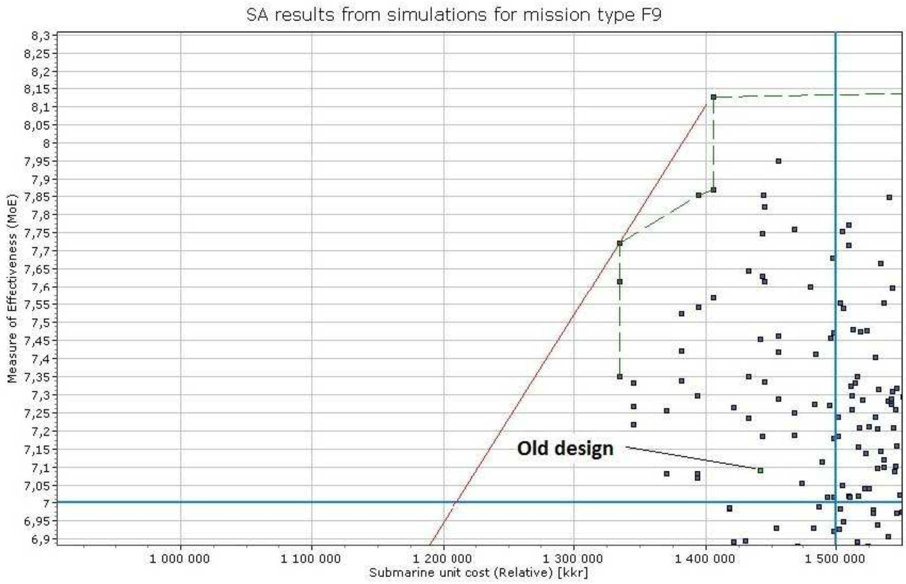

Figure 29: In the zoomed-in design room the possible new design points can be identified and be compared to the submarine type A17 old design point.

When we search for the best design we need to identify the design room for all the different mission types. In the coherent submarine design model, this procedure is repeated for all the relevant different mission types and theirs alternatives. This will result in a 3D chart with the different mission types as the third axis. The result is not a 3D surface but a layered cloud of submarine Play-Cards and/or concepts, where the best Play-Cards and/or concepts for one mission type not necessarily appear as the best design for all other investigated mission types. By identifying the relation between the positions in the chart and the most influential MoPs, a deeper understanding is attained, e.g. the impact of design drivers such as speed, endurance, weapon load, and diving depth etc. on cost and effectiveness. This is how the early knowledge gained by the systems analysis can be fed back to the design loop in search of the best design point.

Finally the decision-maker and customer can interact and together with the design team use the quantitative results from the evaluation with or without preferences for a decision to continue or redirect the design effort following the developed coherent design method for submarine design process depicted in Figure 13.

7. Verifying and validating the method

Showing the validity – usefulness for its purpose – of the coherent method, models and tools through the verification of the individual models in reference projects by design teams in the academic environment, the industry and in the governmental authorities.

7.1 Introduction

Verification and validation is a formal, rigorous and quantitative process based on engineering and mathematical foundations. When large parts of an engineering research project are based on mathematical models and expressions, a straightforward verification process can be applied. All engineering research work cannot be based on mathematical expressions only, according to Pedersen et al. (2000). Several areas are based on both subjective models and mathematical models. One such area is design methods in the engineering design domain. According to Pedersen et al. (2000), validation of design models is an assessment of the usefulness in relation to the purpose of the design method, which can also be expressed in terms of the effectiveness and how efficient the design model is. In this thesis the following definitions are used:

- Verifying — The method calculates the right value within a given range.
- Validating — The method, with its models and methods collectively, gives the right answers to the right questions, and creates the improvement which was the basis for its development, i.e. *usefulness, effectiveness and efficiency*.

7.2 Verifying the models and the method

An overview of the verification of the different models in the coherent method's early phases, i.e. from the study and concept design phase through to the preliminary design phase is given in Table 5 below.

Table 5: Description of different levels in the method and their relationship.

Swedish Defence Material procurements strategy					
Process	ISO/IEC 15288				
Method	A coherent submarine design method for NICS – SubAn				
Models	Needs & functions analysis Verified regarding in- and output data*	Technical systems design Verified See Table 7	Economical systems cost Verified See Table 7	System effect analysis Verified See Table 8	Systems evaluation & analysis Verified regarding in- and output data*
Tools	SubFunc	SubDes	SubCost	SubOA	SubSA
*The models use no mathematical expressions. The methods contain rules for extraction and collection of stated, calculated or measured data. Verification was performed as part of the system design and during acceptance of delivery by each model.					

Verification has been carried out in three rounds; the 2002-2013 round by the FMV and later FOI development team towards specific objects with verifiable results. Some minor adjustments were incorporated as a result of this process. Two additional verifications were conducted by the industry jointly with the FMV development team during the 2007-2009 and 2012-2014 examinations. See Tables 7 and 8 below.

Verification of the various models is non-trivial. Different levels of difficulty exist during verification. At various stages various types of information are used, such as direct data from product sheets, measured results from subcontractors or experiments, processed data from simulation models or direct results from analytical methods. It is easy to be misled into believing that the actual values and results from acceptance trials with submarines would constitute a form of truth. Results from acceptance trials can exist in different forms, from simple answers such as yes or no, measured values to recorded sequences of data for later analysis. In all data, from simulations, model tests or test results, there is a degree of uncertainty. Some of the more dominant uncertainties are described below and in Table 6:

- Physical uncertainty. The uncertainties of physical variables, such as material properties, dimensions and loads. This can be described with frequency distribution functions.
- Statistic uncertainty. Physical quantities can be described with frequency distribution functions that can be determined by sampling what is presented in a histogram, after adaptation of a known frequency function's parameters, against the histogram's statistical data.
    - The physical quantity's real frequency distribution function may differ from the theoretically assumed, especially in the tails of the data.
    - All statistical data consists of a finite number samples. Therefore, there is always an uncertainty about the validity of the statistical data.
- Model Uncertainty. In most models there are some sort of simplifications and generalisations that make it possible to solve problems in analytical studies. These models often contain linearisation of nonlinear problems where the linearisation is valid in an interesting range of the problem definition. In the numerical solutions, there are often simplifications of the geometry to get acceptable calculation times and results.

Table 6: Description of different types of verification and their uncertainties.

Type of verification	**Verification type**	**Description**
Theory	T	Verification of the method used in relation to an accepted theory. Deviations mainly due to round off and numerical simplifications.
Simulation	S	Verification of the method used in relation to an accepted theory. Deviations mainly due to round off and numerical simplifications.
Model tests	M	Verification of the method used in relation to model tests. The deviation can be relatively large since an absolute value (real value) is missing, and the accuracy of measurements and accuracy of execution of tests in this form varies.
Acceptance trials and full-scale tests	P	Verification of models in relation to acceptance trials and full-scale tests. The deviation can be large as the accuracy of measurements and execution for this form of the tests vary.
Real data	R	Verification of the method used in relation to an absolute value. Deviations mainly due to round off and numerical simplifications. Comparable to verification type T above.

Methods have been subject to different types of verification, e.g. the method for hull strength calculation is verified with an accepted theory. This theory is in turn verified with model tests and full-scale tests. In a similar way, other methods are verified. Where uncertainties are large, more than one verification type has been used. For example, the speed-power prediction and manoeuvre tests have both been verified with full-scale results, model tests and simulation results. In situations without reference data, such as the tactical decision-making models, no other verification than the documentation of its rigour and the consistency of the implementation with the intended method has been used. This type of models is instead validated by the use of expert groups.

Verification was performed for the two models for technical system design, SubParm and SubDes, and System cost. These models depend on the following methods, see Table 7 below:

Table 7: Verification results from technical design and system cost calculations.

Verification of the models; Technical design and Systems cost					
Method for:	Verification objects	Ver. type	Allowed deviation	Ver. result	Comments
Hull form[2] (SubParm/Des)	`Volume=f(form)` `Wet surface=f(form)`	T T	0,5 % 1 %	≈0,1 % ≈0,1 %	Elementary and more complex forms have been evaluated.

Static stability[3] (SubParm/Des)	`B= f(form)`
	`G= f(weight)`
	`Depth=f(G&B)`
	`Trim angle=f(G&B)`
	`I=f(waterline area)`
	`M=f(waterline area)`
		T
		T
		T
		T
		T
		T
			0,2 %
			0,2 %
			0,2 %
			0,3°
			1 %
			0,2 %
				≈0,1 %
				<0,1 %
				<0,2 %
				<0,1°
				≈0,1 %
				≈0,1 %
					Calculated for both surfaced and submerged condition, and during transition between surfaced and submerged condition and vice versa.

Pressure hull strength[4] (SubParm/Des)	`σ=f(ODD & geometry)` `CD=f(geometry)`	T T	1 % 1 %	<0,1 % <0,1 %	Deviations against used theory. Production defects included. Theory verified against scale tests.
Speed-power (SubPred)	`Power=f(speed)` `RPM=f(speed)`	P,M,S P,M,S	5 % 2 %	< 5 % < 2 %	Valid speed range is 2-20 knots. Outside this, the error gets gradually larger compared with full-scale test reports.
Power-energy (SubPow)	`Endurance= f(speed, operational routine)`	P	5 %	< 5 %	Endurance is affected heavily by the accuracy of specified efficiency values.
Energy balance (SubEn)	`Auxiliary power= f(speed & operational routine)`	P	5 %	≈ 5 %	Calculated for different operating procedures. See comment above.
Manoeuvring (SubMan)	`Tactical diameter =f(speed, form)` `Time values=f(speed, form) for zig-zag, acc., ret.`	P,M,S	20 % 20 %	≈ 10 % ≈ 20 %	The requirements apply to normal cases. In extreme cases major anomalies have been observed, i.e. nonlinear effects.
Emergency-Manoeuvring (SubRec)	`Time values=f(diving depth) for BT-blowing and pumping`	S,T	20 %	NA[5]	Verification data is missing of type P, M and R. Large influence of nonlinear effects.

Signature (SubSig)	`Passive acoustic sign.= f(speed, operational routine)`
	`Active acoustic sign.= f(form, material)`
	`Magnetic sign.= f(form, material)`
	`Electric sign.= f(speed, form, material)`
		P,M,T	-	-	The different signatures for different operational routines are calculated in SubSig or input to the model.
					To Be observed: SubSig is still under development and under validation.

Cost-prediction[6] (SubCost)	`Cost=f(weight, series effect, index)`	R,T	20 %	≈ 20 %	The discrepancy is due to the difficulty of estimating future index.
Verification type: Real data=R, Full scale tests=P, Model tests=M, Simulations= S, Used theory=T (State of the Art).					

2 Control calculations against theoretical volumes, e.g. sphere, cylinder and composite bodies.
3 Verification by FMV/FOI and industry against a set of complex bodies has shown deviations of ca 0,5 % between calculations and measurements of body displacements. Verification against theory and simple bodies deviates less than 0,1 %.
4 Deviation between theory and model tests are slightly larger and therefore have an impact on set safety factors.
5 Verification data from full-scale tests is not reliable due to the few available tests and the large influence of nonlinear effects.
6 The cost model is based on statistical data from contracts, tenders and RFI/RFQ from 1950 to 2013.

Verification of the operational analysis model for system effect calculations. This model depends on the following methods, see Table 8 below:

Table 8: Results of the verification of the operational analysis model.

Verification of the model for Operational Analysis					
Method for:	Verification objects	Ver. type	Allowed deviation	Ver. results	Comments
Environment	Acoustic environment = f(transmission loss, reverberation, sea noise) Magnetic environment = f(propagation loss, magnetic noise) Electric environment = f(propagation loss, electric noise)	R,M,T	10dB 2dB 2dB	≈10dB ≈2dB ≈2dB	Large variations in measured data. An important requirement on the environmental model is that it is fast in a simulation, some simplifications have been made on the environmental model's accuracy. This has resulted in an approximate environmental model.
Physical movements of actor	Dynamics = f(ship performance)	M,T	5%	<5%	The movement model includes modelling of acceleration, retardation, deep change, yaw rate, etc. Within the linear area of response.
Power-energy	Power consumption = f(speed, operational routine)	P,M,T	5%	<5%	Deviation depends largely on the accuracy of test data and model tests.
Signature	Passive acoustic sign.= f(speed, operational routine) Active acoustic sign.= f(form, material) Magnetic sign.= f(form, material) Electric sign.= f(speed, form, material)	P,M,T	-	-	The different signatures for different operational routines are input to the model. See also Table 7.
Surveillance	Detection = f(sensors, environment, signatures)	M	25%	<25%	Sensor performance is crucial for the outcome in combination with the corresponding signatures.
Tactical decision	Tactics = f(mission order, surveillance, command & control, CO-model, stores, performance, pay-load)	M,T	-	-	The tactical model is an events driven model that reacts on events during the simulation cycle. The tactical decision-making chain is developed based on experience/theories and answers from interviews of commanding officers and executive officers. The method has been validated.
Hit calculation	Hit = f(weapons, sensors, form, Countermeasures)	M,T	5%	5%	
Survivability	Survivability = f(weapons, material)	M	25%	<25%	The outcome could be unhurt, damaged or sunk.
System effect	System effect = f(mission type, environment, data elements, measure elements, calculation element)	T	-	-	Analytical calculation. Relative measure. The method is validated.
Systems capability	Systems capability = f(action, endurance, signature, survivability)	T	-	-	Analytical calculation. Relative measure. The method is validated.
Verification type: Real data=R, Full scale tests=P, Model tests=M, Simulations= S, Used theory=T (State of the Art).					

The models and their methods (Tables 7 and 8) have been verified and validated and approved for use following verification and adjustments.

7.3 Validation of the coherent method

Validation of the coherent design method is a question of usefulness for its purpose based on credibility and trust. The challenge is to show this scientifically convincing. This is done through the process of the validation square with the active involvement of participating groups with the opportunity to report their experience to the development team of the method. Validation has been done by various participating groups from both the academic side as from industry and authorities. These groups have tested and validated the toolbox on several occasions. Validation has been carried out with Swedish submarines but also through inverse modelling of own and internationally known submarines, that is, by making use of available information and known conditions, it is possible to go backwards in the design process to recreate the form, function and performance of a submarine system.

An important factor in the validation process was access to participating groups from both the academic and industrial world. This form of validation provides significant qualitative comments for improvements of the method. The validation has been completed in batches of four different participating groups at four different occasions. Round 1: Group 1a and 2a, Round 2: Group 1b and 2b, Round 3: Group 3 and 4 and Round 4: Group 4. The groups were:

1. The author together with development team (FMV/FOI) based on the described method presented by Nordin (1990) in comparison with the previous sequential design method (a: 1991-2001 and b: 2002-2013).
2. Operational commanders and executive officers serving with or having served with the submarine squadron together with the author and the development team (a: 1993-2001 and b: 2003-2012).
3. Design groups, during training at CTH/FOI/FMV in the academic environment with the following objectives (2003-2013):
   a. To learn the new method.
   b. To utilise the method on a design project.
   c. To report comments and experiences to the author and the design team.
4. The active design teams at FMV/FOI and expert design teams in industry. In this group the developed method has been used in the following ways (2005-2012 and 2013-2014):
   a. FMV design team to conduct analyses and develop submarine concepts for HTU of A19S and for the development of submarine A26 in their early phases.
   b. FMV design team to follow up on the industry's results for HTU of A19S and the A26 and to compare with own results during the following phases.
   c. The industry's expert and design teams.
      - To learn and make use of the method in parallel with their own method.
      - To validate, compare, evaluate and report experiences.

The validation was carried out by the four groups regarding the following aspects in comparison with the previous type ship method:

- Overall view of the design problem, integrated calculation and analysis environment.
- Faster and earlier results.
- Better precision in the calculations, although they occur in earlier phases.
- Increased and steeper growth of knowledge content earlier in the project.
- Working methods and the availability of information about the design object.

The four validating rounds (Groups 1, 2, 3 and 4 during the period 2002-2014) reported suggestions for modifications to the models so that they would be more consistent with the coherent design method, especially regarding support for mission analysis (functional analysis) and 3D presentation of Play-Cards for better visualisation and to work more interactively in 3D with a concept. This also includes 3D support for evaluation and presentation of operational analysis results in the systems analysis model in the search of the best design solutions. These suggestions were developed and most have been implemented into the coherent method. After validation, all the groups have reached the same results, namely that the new coherent design method in relation to the previous method:

- Contains major necessary elements of design.
- Provides a gradual and traceable knowledge growth from initial idea to a finished systems definition.
- Generates greater knowledge growth with higher precision earlier in the process.
- Generates larger knowledge content without locking or hampering the creativity.
- Is both exploring and educative.
- Is useful for its purpose.

To summarise, the result corresponds well to the stated hypothesis and stated model issues in chapter 3. As can be seen in Figure 30, with the help of the coherent method and the toolbox, project teams of 2-5 designers tested the design method from preparations to reporting, and one may conclude that:

- Play-Cards can be automatically developed within a few seconds and if needed further refined in minutes to an hour by the designer.
- Concepts can be developed in a day.
- Reference models can be developed in 1 to 5 working days.
- Product models can be developed in 6 to 30 working days.

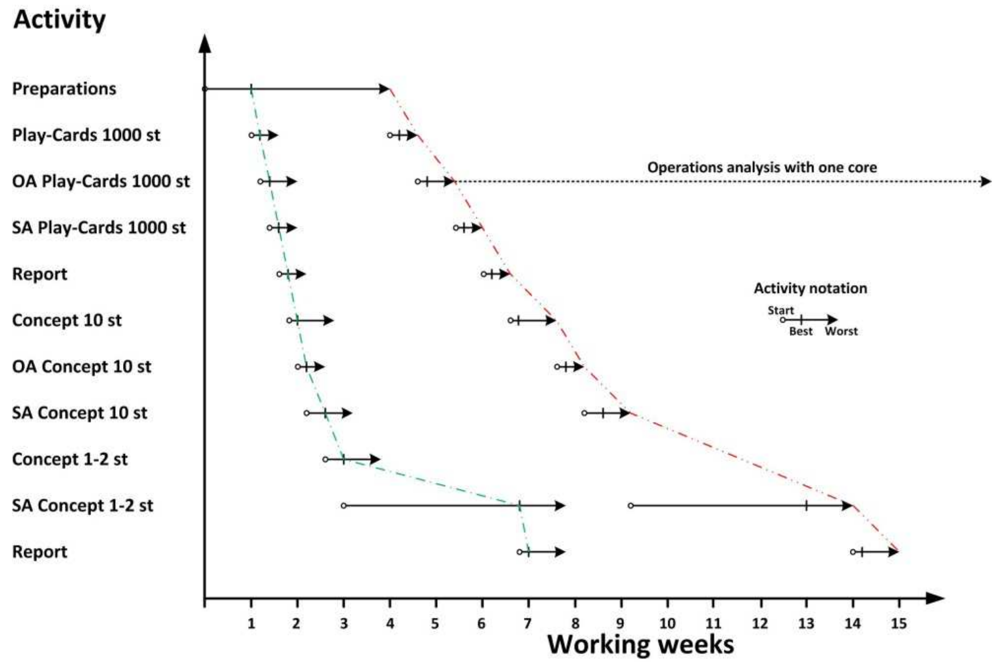

Figure 30: Lead-times for the coherent design method. The curves represent submarine designers (team of 2-5) best and worst lead-times, respectively.

This, the exploration of the design room with 1000 feasible and balanced Play-Cards that where evaluated both from a system cost and system effectiveness perspective, including design of 10 selected and refined concepts, shall be compared to the older method where just one concept took between 4 to 12 weeks to design but still with uncertainties regarding the fundamental submarine balances.

Submarine Play-Cards are used to find the best design points with the help of operational analysis and cost estimations in the functions domain, supported by a systems analysis model for evaluation and selection for further development of submarine concepts in the systems domain. Submarine concepts, which are based on identified design points developed using the new coherent method, were found complete with a representative description of the technical design, economic calculation and system effect so that they could be assessed vis-à-vis alternative concepts developed in relation to stated needs.

Initially, several ambiguities were found in connection with reverse engineering. The ambiguities have been explained and were traced to actual errors in the real system design descriptions. These could be attributed to errors in calculations, e.g. of the submarine's endurance, which in turn was due to bad data for the submarine's energy consumption and storage in the models used in the old method. These errors were attributable to incorrectly specified efficiencies at different part loads for various operating routines relative to the specified storage sizes. The documented experience has led to a reduction of the possibility of similar errors occurring in the future. Lead-times for a submarine project that use the new coherent method were found to be very sensitive to the lead-times for OA. Initially only two core computers were used, see Figure 30, which led to too long lead-times. Using an appropriate number of cores working in parallel, e.g. 25 to 100 cores, it straightforward to bring the OA lead-time in parity with other project activity times.

The different validation activities have followed the procedure and steps of the validation of design methods introduced by Pedersen et al. (2000), i.e. the validation square, see Figure 11 and the four validation cases on page 26.

Finally the validation work through the process of the validation square with the use of participatory design teams from academia, governmental authorities and industry was successful. Validation through reengineering existing submarines, and creating new designs from stated needs, has proved the usefulness of the developed coherent design method for the purpose of submarine design in the early phases. The new coherent method is now in use by the Swedish defence authorities.

8. Discussion, conclusions and future work

Relates to and answers the original general question with its research and model questions and presents conclusions of the work. Discusses the problems of the development of methods and tools for Naval Integrated Complex Systems whose functional requirements and cost first is clarified through the interaction with an active environment. Shows how to generalise the coherent method to other integrated complex systems and thereby the sustainability of the method. Suggests areas for further research.

8.1 Discussion

The design process for submarine systems in Sweden has until now been characterised by fragmentation in the early stages and an absence of a coherent method with integrated tools in the early phases. Development of submarine concepts has in general followed the design spiral which is why it could take months to generate a balanced technical submarine concept. No continuous linked cost calculation or system effect assessment was performed in the early stages but were instead used as a control station at the end of each phase. All this gave rise to a fundamental question when this project was launched.

Why is it that the existing knowledge of naval architecture with its systems view on system design and cost, including operational analysis, is not utilised in a coherent method for the design of Naval Integrated Complex Systems?

The general question was explored with the help of research questions (RQ1-RQ5) see Chapter 3. To these a hypothesis was formulated. Together with the development of the research questions the method issues were discussed and formulated. These structured preparations have guided the development of a new coherent method, containing models and methods that has been tested and validated.

Research questions can be answered through the method issues in the the new coherent method in search of best designs, in which the frame of reference and the conclusions of studies form the basis. The answers to the research questions are:

- RQ1: Through a coherent method that span over deduction of needs and design of requirements based on technical system design, cost calculations, operational analysis and systems analysis for evaluation and selection in search of the best design, it is now possible already in the early phases to develop feasible and balanced designs that correspond to the needs.
- RQ2: By continuously, within the coherent method, performing cost predictions and economic risk assessments, a good estimate on the cost of production can be reached.
- RQ3: By continuously, within the coherent method, utilising operational analysis methods for system effectiveness calculation for the relevant scenarios, the system effect can be evaluated for the design object.

- RQ4: By continuously, within the coherent method, evaluating alternative Play-Cards and concepts and feed the results of the technical system design, its cost and system effect into the systems analysis, the search for the theoretically most cost-effective concept can be convincingly carried out. In the end, the interpretation of cost-effectiveness is closely connected to the preferences of the customer and stakeholders.
- RQ5: Given the answer to RQ1, it is possible to design and present quantitative data that correspond to the needs. By involving the decision-makers and their preferences in the selection process we assure acceptance of the selected best design.

The coherent method introduces a new approach based on a representation of a submarine, the Play-Card with its system functions and functional volumes, and by connecting cost predictions and operational analysis results to the technical system design in the functions domain in the early phases. As a result, the coherent method can use design methods used down-stream in the design process and OA as a tool early in the design effort by using design objects such as Play-Cards from the functions domain. As a result, the deduced functional requirements can be identified and extracted from the OA simulations with the help of a mission analysis model, and when implemented in the coherent method, a balanced set of requirements for the concept design based on evaluated Play-Cards can be set. This new application of OA is a further development of the mission based functional analysis.

An important contribution to system design of physically large & complex systems is the ability to combine models of technical system design with models of operational analysis and system effect early during development. Operational analysis methods, given a design object, together with methods for functional analysis provide an opportunity to identify functional requirements which are not directly possible to extract from a functional analysis that is based on a planned mission and known behaviour.

It is only when a design object is confronted with an active environment that the tactical function needs and their functional performance is brought to the surface and can be quantified. It is therefore important for the mission analysis part of the functional analysis that it is based on both planned behaviour according to a mission description and on an event-driven tactical behaviour when the design object meets its operational environment.

The method is developed for integrated complex systems where functionality and functional requirements cannot properly be deduced from the needs without having a valid design object to simulate the influence on it from its surrounding operational environment. In the general case, the method must be supplemented with methods and tools for each respective domain.
The general idea with a coherent method can be utilised when designing railway systems, power stations etc. when the interaction with the surrounding environment needs to be integrated in the overall design of a solution.

8.2 Conclusions

Early studies (Nordin, 1990 & 2009) have shown deficiencies in the Swedish design process for submarine systems. Based on the frame of reference and the hypothesis, a coherent method for initial design was developed, encompassing technical system design, cost calculations, system effectiveness calculation, and system evaluation and selection. The coherent method makes it possible to create an integrated design and analysis environment for efficient work in the early phases during initial design.

The concept exploration model within the coherent design method makes it possible to search for best designs in the design room by working with models in the functional domain. Based on identified and deduced needs and designed requirements in combination with the customer and stakeholders preferences, the best satisfying designs can be determined amongst the Play-Cards and concepts.

The models used in the coherent method have been verified internally in several steps. The models have also been examined and verified by design teams in industry and research institutions. In all cases, this has led to successful results.

The coherent method was validated by designing new submarines from stated needs and reengineering five reference projects with different styles, including both ADP and AIP submarines. Validation of the coherent method and its models has demonstrated good results. The coherent method shows validity and the validation process generated new knowledge about the reengineered reference projects.

There are four main approaches contributing to the realisation of the coherent method in this thesis based on the introduction of a representation of a submarine, the Play-Card with its system functions and functional volumes.
Firstly, there is an integrated domain driven design approach for a technical description of the design object, the related system cost and system effect.
Secondly, the uses of a generic design object to stimulate the operational analysis simulation to extract tactically driven system functions and functional requirements.
Thirdly, the use of a synthesised operational environment, i.e. a war gaming event based Monte Carlo OA simulation model including tactical and behavioural rules in establishing the design objects' system effectiveness under diverse conditions.
Fourthly, the utilisation of the combined set of tools to provide the designer with the capability to generate, explore and analyse a large number of competing feasible Play-Cards and concepts in search of best satisfying designs and designing sets of affordable and balanced requirements .

Finally, based on these main contributions, three beneficiary aspects in the early phases were apparent during the validation of the coherent method; *first,* the integrated computation and analysis environment saved time in the generation of submarine Play-Cards and concepts, *second,* their greater knowledge content and *third,* the higher level of precision in calculations earlier in the process.

From an industrial perspective the developed coherent method, with its models, methods and tools, can be used to explore the design space and significantly speed up submarine system development and to get more precise and accurate results in the early phases compared to the previously used Swedish method. The coherent method has been proven to be *useful* for the purpose of defining and designing submarines in the early phases of design.

8.3 Future work

In a world where interactions are becoming more frequent and more intense, it is no longer realistic to continue with simplistic models for design of complex integrated systems. As systems theory and systems engineering have evolved they have resulted in cross-disciplinary and multidisciplinary approaches and strengthened naval architecture and ship design. In this thesis, a possible solution for a coherent method for Naval Integrated Complex Systems in search for the best satisfying designs has been presented. There is a need for continued research in the field of NICS in the following areas:

- The organisation's development and adaptation to work rationally with NICS.
- Further development and exploitation of an affordable and more rational requirement elucidation process between agencies and industry with the use of parallel processes and multi-tasking for faster convergence towards a balanced design point.
- How to efficiently handle refinements of evolutionary driven scripted descriptions of properties and form.
- Refinements of physically described event-driven operational analysis models.
- The development of a more general interpretation of NICS so that the basis for the coherent method can be used in other areas when planning and designing physically large integrated and complex systems.

This thesis has presented a new coherent method for the design of NICS, exemplified with submarines. The general application of this method in other areas has been touched upon. A modern submarine is of course first of all designed to be very effective in crisis and war but it also needs to be reasonably environmentally friendly during its operational use in peacetime, and at its end of technical life time be scrapped without damage to the environment.

In this dualism lies a challenge for the design team. To be able to design a war machine with high system effect and at the same time meet the rules and requirements for a sustainable world. As in all design activities this will be a compromise where the governmental system will set the level of ambition so not to hamper the usability in war while minimising negative effects on the environment. This balance needs to be continuously monitored and developed in order to strive for a sustainable future.

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