NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

AC/323(SAS-076)TP/430

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RTO TECHNICAL REPORT **TR-SAS-076**

NATO Independent Cost Estimating and the Role of Life Cycle Cost Analysis in Managing the Defence Enterprise

(Estimation indépendante des coûts de l'OTAN et rôle de l'analyse des coûts globaux de possession au sein de l'OTAN)

This Report presents the findings of Task Group SAS-076.

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The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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List of Acronyms

AAS	Amphibious Assault Ship
ACES	Advanced Cost Estimating Systems
AESA	Active Electronically Scanned Array
AGBP	Average Global Bunker Price
AGS	Alliance Ground Surveillance
AOR	Auxiliary Oiler Replenishment
APN	Air Procurement Navy
AST	Acquisition Support Team
ASTOR	Airborne Stand-Off Reconnaissance
BIX	Bunker Index
BWB	Federal Office of Defence Technology and Procurement (German)
BWI	Bunkerworld Index
BY	Budget Year
C2ISR	Command, Control, Intelligence, Surveillance and Reconnaissance
CAD	Canadian Dollar
CAIG	Cost Analysis Improvement Group
CAPE	Cost Assessment and Program Evaluation
CARD	Cost Analysis Requirement Description
CATLOC	Systecon Costing Software
CBS	Cost Breakdown Structure
CER	Cost Estimating Relationship
CIB	CDL Interfacebox
Civ	Civilian
CIWS	Close-In Weapon System
CLM	Contractor Level Maintenance
CLS	Contractor Logistics Support
CM	Corrective Maintenance
CMMI	Capability Maturity Model Integration
CORA	Centre for Operational Research and Analysis
cp	controllable pitch
CSOP	Command Standard Operating Procedure
CV	Coefficient of Variation
CY	Constant Year
DADD	Data and Assumptions Document Definition
DAMA	Demand Assigned Multiple Access
DDQ	Design, Development and Qualification
DGPS	Differential Global Positioning System
DLM	Depot Level Maintenance
DoD	Department of Defense (U.S.)
DRDC	Defence Research and Development Canada
ECM	Electronic Countermeasures Systems
EFV	Expeditionary Fighting Vehicle
ELINT	Electronic Intelligence
EO/IR	Electro-Optical/Infra-Red
eSBM	enhanced Scenario-Based Method
ESLOC	Equivalent Source Lines Of Code

ESM	Electronic Support Measures
EUR	Euro
fp	fixed pitch
FREMM	FREgate Multi-Mission (French)
FRP	Full Rate Production
FV	Future Value
FY	Fiscal Year
G&A	General & Administrative
GBP	(Great Britain) Pound Sterling
GCBS	Generic Cost Breakdown Structure
GMTI	Ground Moving Target Indicator
GPS	Global Positioning System
GS	Ground System
HMS	Her Majesty's Ship
HNMS	Her Netherlands Majesty's Ship
hrs	hours
I&T	Integration & Test
IATC	Integration, Assembly, Test and Checkout
ICE	Independent Cost Estimate
IFF	Identification Friend or Foe
ILM	Intermediate Level Maintenance
ISR	Intelligence, Surveillance and Reconnaissance
JSTARS	Joint Surveillance Target Attack Radar System
kts	knots
LAV	Light Armoured Vehicle
LCAC	Landing Craft, Air-Cushioned
LCC	Life Cycle Costs
LCM	Landing Craft, Mechanized
LCPL	Landing Craft, Personnel, Large
LCS	Learning Curve Slope
LCU	Landing Craft, Utility
LCVP	Landing Craft, Vehicle, Personnel
LOS	Line-Of-Sight
LPD	Landing Platform Dock
LPH	Landing Platform Helicopter
LRE	Launch and Recovery Element
LRIP	Low Rate Initial Production
LRU	Line Replaceable Unit
LSD	Landing Ship Dock
LSE	Logistic Support Elements
LVT	Landing Vehicle, Tracked
m	meters
M	Million
MCE	Mission Control Element
MDAL	Master Data and Assumption List
MGCS	Mobile General Communications Stations
MGGS	Mobile General Ground Stations

Mil	Military
mm	millimeters
MOB	Main Operating Base
MORS	Military Operational Requirement
MOS	Main Operating Station
MP-RTIP	Multi-Platform Radar Technology Insertion Program
MS	Milestone
MT	Metric Ton
MTBF	Mean Time Between Failures
MW	Mega Watts
NAC	North Atlantic Council
NAGSMA	NATO Alliance Ground Surveillance Management Agency
NAGSMO	NATO Alliance Ground Surveillance Management Organisation
NATO	North Atlantic Treaty Organisation
NAVSEA	U.S. Naval Sea Systems Command
NBCD	Nuclear, Biological, and Chemical Defence
NCCA	U.S. Naval Center for Cost Analysis
NGISSI	Northrop Grumman Integrated Systems Sector International
NME	Navy Maintenance Establishment
nmi	nautical mile
NOK	Norwegian Krone
O&S	Operational & Support
OCCAR	Organisation for Joint Armament Cooperation (French)
OECD	Organisation for Economic Co-operation and Development
OLM	Organizational Level Maintenance
OTS	Off-The-Shelf
PAPS	Phased Armaments Programming System
PBM	Panel Business Meeting
PCA	Principal Component Analysis
PfP	Partnership for Peace
PHST	Packing, Handling, Storage, and Transporting
PM	Preventive Maintenance
PM	Program Management
PMoU	Program Memorandum of Understanding
POL	Petroleum, Oil, Lubricant
PPP	Purchasing Power Parity
PSE	Peculiar Support Equipment
PV	Present Value
RADAR	Radio Detection And Ranging
RAMS	Reliability, Maintainability and Supportability
RAP	Raw Aircraft Procurement
RF	Radio Frequency
RFA	Radio Frequency Assembly
RNLN	Royal Netherlands Navy
RTB	Research & Technology Board
RTO	Research & Technology Organisation
RWR	Radar Warning Receiver
SAM	Surface-to-Air Missile
SAR	Synthetic Aperture Radar

SAS	Systems Analysis and Studies
SAS-054	NATO RTO SAS-054
SAS-076	NATO RTO SAS-076
SATCOM	Satellite Communications
SDD	System Development and Demonstration
SE	Systems Engineering
SEK	Swedish Krona
SoI	System of Interest
SONAR	Sound Navigation And Ranging
SSM	Surface-to-Surface Missile
STAM	Strategy-to-Task Model
TACAN	Tactical Air Navigation
TCAS	Traffic Collision Avoidance System
TGGS	Transportable General Ground Stations
TOA	Total Obligation Authority
TSPR	Total System Performance Responsibility
TY	Then Year
U.S.	United States
UAV	Unmanned Aerial Vehicle
UCE	Command and Control Elements
UHF/VHF	Ultra High Frequency / Very High Frequency
USD	United States Dollar
USSOCOM	United States Special Operations Command
VAMOSC	Visibility and Management of Operating and Support Costs
WAP	Weighted Aircraft Procurement
WBDL-LOS	Wideband Datalink Line-Of-Sight
WMA	Wideband Modem Assembly
Y/N	Yes/No

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NATO Independent Cost Estimating and the Role of Life Cycle Cost Analysis in Managing the Defence Enterprise

(RTO-TR-SAS-076)

Executive Summary

At its October 2006 Panel Business Meeting (PBM), the Systems Analysis and Studies (SAS) Panel established an Exploratory Team (ET.AY) to propose new life-cycle cost estimating activities as follow-on to the SAS-054 Task Group on Methods and Models for Life-Cycle Costing. SAS-054, in turn, built on the work of SAS-028, which had developed a generic cost breakdown structure. In addition to this work a code practice was developed by SAS-069. One of the activities the Exploratory Team recommended, as the next logical phase that would build upon the efforts of SAS-028 and SAS-054, is to prove the concepts of these earlier RTO SAS works on Life Cycle Cost Analysis by rigorously applying the guidelines to generate sound, reliable, Independent Cost Estimates (ICE) of a major weapon system acquisition programs of current, international interest:

- HMS Rotterdam and HMS Johan de Witt Landing Platform Docks (LPD) of the Netherlands; and
- NATO's Alliance Ground Surveillance System (AGS).

Life-cycle cost estimates of defence acquisition programs are inherently uncertain. Estimates are sometimes required when little if any of a program's total cost is known. Years of system development and production, and decades of operating and support costs, need to be estimated. Estimates, in turn, are based on historical samples of data that are almost always messy, of limited size, and difficult and costly to obtain. Further, key characteristics of the system may actually change as the system proceeds through development and even production. Increases in system weight, complexity, and lines of code are commonplace. Innovative, pioneering statistical techniques were employed in these efforts that pushed the state of the art in cost analysis to new frontiers:

- Decision trees, regression models, and hierarchical clustering, based on scores of technical and performance characteristics, to estimate ship acquisition costs. The task group produced the paper "An Application of Data Mining Algorithms for Shipbuilding Cost Estimation" which won "Best Paper" in the Applications Track at a major international symposium and was published in professional literature.
- Benchmark coefficients of variation coupled with a point estimate to generate a cumulative probability distribution of cost, or S-curve, for NATO AGS. This work resonated strongly throughout the defence cost community and directly supported the Alliance's acquisition of this critical asset.

SAS-076 also ventured into the realm of defence planning and acquisition. Every NATO and **Partnership for Peace (PfP)** Nation has its own procedures and processes for establishing national security guidance and objectives; for identifying military needs; and for developing and procuring solutions. Within the context of this mélange of national norms, SAS-076:

- Conducted an international conference on capability portfolio analysis;
- Captured commonalities and differences in national processes and procedures; and
- Recommended a set of best practices in the cost-analysis domain.

By working as a cohesive team under the aegis of the Systems Analysis and Studies Panel, SAS-076 demonstrated that strong results can be achieved and significant value added for the entire NATO and PfP defense community.

Estimation indépendante des coûts de l'OTAN et rôle de l'analyse des coûts globaux de possession au sein de l'OTAN

(RTO-TR-SAS-076)

Synthèse

Lors de sa réunion d'octobre 2006, la Commission, sur les Etudes et l'Analyse de Système (SAS) a créé l'Equipe exploratoire (EE.AY) en vue de proposer de nouvelles activités pour l'estimation des coûts globaux de possession dans le prolongement du groupe de travail SAS-028 sur les méthodes et les modèles d'évaluation des coûts globaux de possession. A son tour, SAS-054 s'est appuyé sur les travaux de SAS-028, qui avait développé une structure générique de ventilation des coûts. En complément de ce travail, SAS-069 avait développé un code de bonnes pratiques. Une des activités recommandées par l'équipe exploratoire, considérée comme phase suivante logique s'appuyant sur les efforts réalisés par SAS-028 et SAS-054, consiste à démontrer la validité des concepts de ces travaux préliminaires relatifs à l'analyse des coûts globaux de possession en se basant sur une application rigoureuse des directives, en vue de produire des Estimations de Coûts Indépendantes (ECI) justes et fiables concernant des programmes d'acquisition d'un système d'arme principal d'envergure internationale et actuelle :

- Les plateformes d'atterrissage du HMS Rotterdam et du HMS Johan de Witt des Pays-Bas ; et
- Le système de surveillance terrestre *Alliance Ground Surveillance* (AGS) de l'OTAN.

Les estimations des coûts globaux de possession des programmes d'acquisition de défense sont par nature incertaines. Ces estimations sont parfois nécessaires lorsque le coût total d'un programme n'est connu qu'en infime partie ou pas du tout. Les années dédiées au développement du système et à la production, ainsi que les coûts d'exploitation et de soutien sur des dizaines d'années doivent être évalués. Les évaluations, à leur tour, sont basées sur un échantillonnage de données historiques qui sont la plupart du temps désordonnées et de faible volume, et par ailleurs difficiles et coûteuses à obtenir. En outre, les caractéristiques principales du système peuvent en fait évoluer en fonction de la progression du système dans la phase de développement et parfois même de production. L'augmentation du poids, de la complexité et des lignes de code du système est courante. Des techniques statistiques innovantes et pionnières ont été intégrées dans ces travaux qui ont fait reculer les limites d'une analyse des coûts à la pointe du progrès :

- Les arbres décisionnels, les modèles de régression, et le regroupement hiérarchique, basés sur de nombreuses caractéristiques techniques et de performance, pour réaliser l'estimation des coûts d'acquisition d'un navire. Le groupe de travail a rédigé un document intitulé « Application des algorithmes d'extraction de données pour l'estimation des coûts dans la construction navale » qui a remporté le prix du « Meilleur Document » dans les Orientations d'Applications lors d'un grand symposium international, et qui a été publié dans des ouvrages spécialisées.
- Les coefficients de référence de la variation associée à une estimation ponctuelle en vue de générer une distribution stochastique cumulative du coût, ou courbe en S, pour l'AGS de l'OTAN. Ces travaux ont eu un impact important à travers toute la communauté chargée des coûts de défense et ont apporté un soutien direct à l'Alliance dans sa démarche d'acquisition de ce système critique.

SAS-076 s'est également aventuré dans le vaste domaine de la planification et l'acquisition de défense. Chaque membre de l'OTAN et du **Partenariat pour la Paix (PpP)** possède ses propres procédures et processus pour l'établissement des orientations et des objectifs en matière de sécurité nationale ; l'identification des besoins militaires ; et le développement et l'approvisionnement en solutions. Dans ce contexte de diversité en termes de normes nationales, SAS-076 :

- A organisé une conférence internationale sur l'analyse de l'éventail des capacités ;
- A collecté les similitudes et les différences entre les procédures et les processus nationaux ; et
- A recommandé un ensemble de bonnes pratiques à respecter dans le domaine de l'analyse des coûts.

Sous la supervision de la Commission sur les Etudes et l'Analyse de Système l'équipe SAS-076 a réalisé un travail d'ensemble et a démontré qu'il était possible d'obtenir des résultats de qualité et d'apporter une valeur ajoutée significative à l'ensemble de la communauté de défense de l'OTAN et des états du PpP.

NATO Independent Cost Estimating and the Role of Life Cycle Cost Analysis in Managing the Defence Enterprise

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1.0 INTRODUCTION

1.1 Background

Life-cycle cost estimates of defense acquisition programs are inherently uncertain. Estimates are often required when only 5% of a program's total cost is known. Years of system development and production, and decades of operating and support costs, need to be estimated. Estimates, in turn, are based on historical samples of data that are almost always messy, of limited size, and difficult and costly to obtain. Herculean efforts are commonly required to squeeze usable information from a limited, inconsistent set of data. And no matter what estimation tool or method is used, historical observations never perfectly fit a smooth line or surface but instead fall above and below an estimated value. To complicate matters, the weapon system or automated information system under study is often of sketchy design. Only limited programmatic information may be available on such key parameters as schedule, quantity of units to be bought, performance, requirements, acquisition strategy, and future evolutionary increments. Further, key characteristics of the system may actually change as the system proceeds through development and even production. Increases in system weight, complexity, and lines of code are commonplace.

For all of these reasons, a life-cycle cost estimate, when expressed as a single number, is merely one outcome or observation in a probability distribution of costs. That is, the estimate is stochastic rather than deterministic, with uncertainty and risk determining the shape and variance of the distribution.

Given the difficult job of producing credible, cradle-to-grave cost estimates in a highly stochastic acquisition and estimating environment, SAS-054 has developed a guideline to conduct a life-cycle cost analysis in a multi-national environment. SAS-076 then sought to establish a new mode of cooperative working within the international cost-estimating community. Hitherto, nations have often developed, by themselves, life-cycle cost estimates for acquisition programs of mutual or collaborative interest.

The vision of SAS-076 is that by working together in the cost-estimation process, NATO and PfP nations will all hopefully benefit from a cross-fertilization of ideas, data, experiences, perspectives in multi-national projects.

1.2 Provenance and Approval

The NATO Research & Technology Organization (RTO) System Analysis and Studies (SAS) Task Group SAS-054 (Methods and Models for Life Cycle Costing) published guidelines for conducting life cycle costing analysis within the NATO nations [1]. Their comprehensive report provided an extensive review of cost forecasting methods and models, including the two most critical elements for any viable forecasting analysis: data collection and the measurement of uncertainty and risk. One of the key recommendations of the study "... would be to demonstrate the proof of concept (methods and models) described in the report by using a practical application of the guideline".

At its October 2006 Panel Business Meeting (PBM), the Systems Analysis and Studies (SAS) Panel established an Exploratory Team (ET.AY) to propose new life cycle cost estimating activities as a follow-on to SAS-054[1]. The Exploratory Team was established to determine the feasibility of conducting an independent cost estimate (ICE) of a major weapon system acquisition programme of current international interest. Candidate systems discussed by the team members included NATO AGS, NATO's multi-mission aircraft, A400M, the European multi-mission frigate, FREMM, amongst others. Within a year of establishment, the team found just how hard it was to get approval from national consortia to develop an ICE for a major acquisition programme.

[1] SAS-054, in turn, built on the work of SAS-028 which had developed a generic cost breakdown structure.

Rejection notes were received confirming that no approval could be given involving a study on FREMM and A400M. However, approval was received for the team to conduct an ICE on the NATO AGS programme, and eventually, for the Royal Netherlands Navy Landing Platform Dock Rotterdam class amphibious warfare vessel and the Canadian LAV III, light armoured vehicle.

The Exploratory Team recommended a third and logical phase that would build upon the efforts of SAS-028 and SAS-054:

- Implement best life cycle costing practices, as defined in the work of SAS-054, by rigorously applying them to generate a sound, reliable independent cost estimate (ICE) of a major weapon system acquisition programme of current, international interest. This will demonstrate proof of concept of the guidelines.
- Identify best practices in capability portfolio analysis, with an emphasis on the role of cost analysis in the process.

NATO's Research and Technology Board (RTB) approved these recommendations in the Spring of 2008 and stood-up SAS-076 to implement them. In June 2008, the first meeting of SAS 076, *NATO Independent Cost Estimating and its Role in Capability Portfolio Analysis*, was held in Rome, Italy.

1.3 Objectives

Study objectives were defined as follows:

- Independent Cost Estimates (ICEs)
  - Choose one or more existing systems for which there is a CARD (Cost Analysis Requirements Description - used in the U.S.) or an MDAL (Master Data and Assumptions List - used in the U.K.) and for which actual cost data exist for development, production and in-service.
  - Generate an independent cost estimate based on the SAS-054 guidelines for best practice, using the CARD or MDAL as it existed at the start of the acquisition program.
  - Analyze risks and uncertainties.
  - Generate costs over the life cycle.
  - Obtain information on the actual cost of the weapon system under study, if available. Tally and analyze differences between actuals and estimates, thus providing invaluable feedback on the accuracy and completeness of the guidelines.
  - Provide a complete, documented analysis for both ex-post and ex-ante cost estimation to decision makers.

  Through these activities, the cost estimating concepts of the guideline developed in the SAS-054 study activity were to be demonstrated and validated, including the methods, models and processes.

- Role of Cost Analysis in Managing the Defense Enterprise

  Most defense establishments are quite adept at measuring the cost and the value of a specific program to fulfill a specified mission. Trade-offs are conducted. Analyses of alternatives are studied. Sometimes, gap analysis is done. But are comparisons made program versus program with an emphasis on the best way of meeting national and coalition objectives? Portfolio analysis is a promising method to improve defense business practices by analyzing a group of systems as a whole rather than focusing on acquisition programs one at a time.

  Specific objectives of SAS-076 were to:

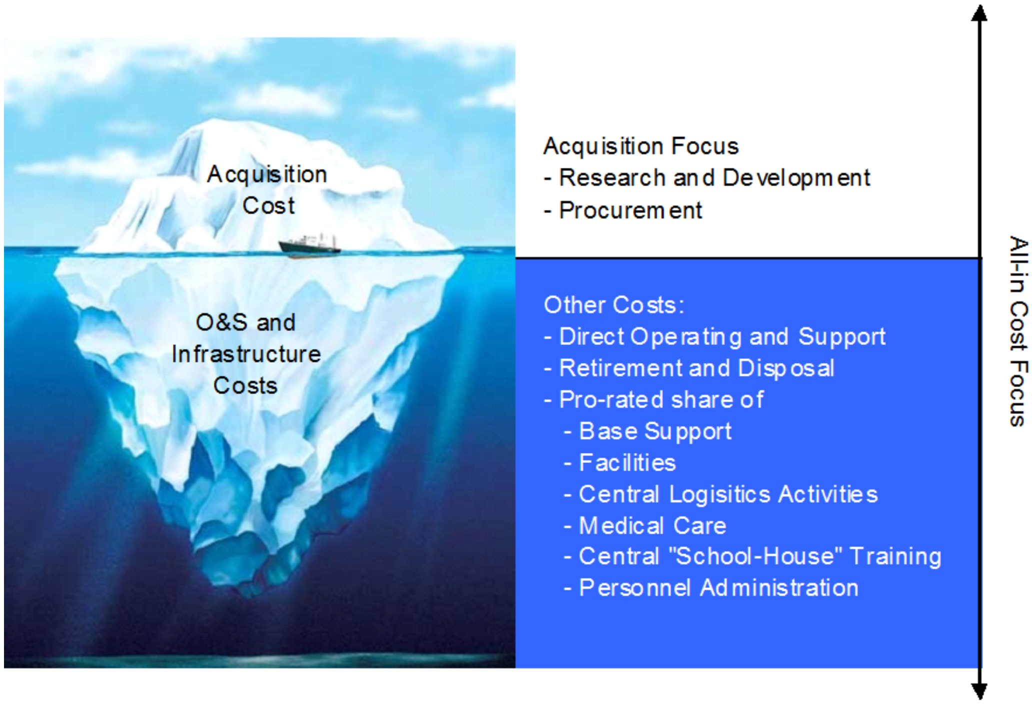

Figure 1: The life cycle cost iceberg

– Identify commonalities and differences among NATO and PfP nations in executing capability portfolio analysis, especially with respect to the use of life-cycle cost analysis.

– Recommend best practices regarding the analysis of risks and uncertainties of costs, capabilities, and requirements, thus engendering more informed decision-making on the allocation of scarce defense resources.

1.4 Scope

ICEs were generated for these acquisition programs:

- NATO Alliance Ground Surveillance System (AGS)
- Royal Netherlands Navy Landing Platform Dock (LPD): HMS Rotterdam and HMS Johan de Witt

Within the domain of total ownership costs shown in Figure 1, the primary focus of the ICEs was estimation of acquisition costs, and, in some cases, operating and support costs. Infrastructure costs were beyond the scope of this effort. Details on the AGS ICE are presented in Annex A. Details on the Netherlands LPD ICEs are presented in Annex B1 and B2.

The effort in capability portfolio analysis was expanded to include an investigation of the role played by life-cycle cost analysis in managing the entire defense enterprise, as shown in Figure 2 [2]. Details are presented in Annex C.

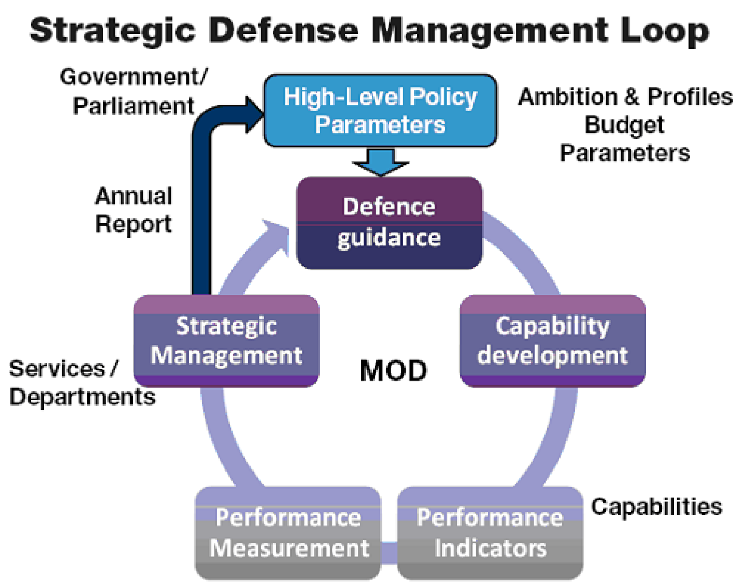

Figure 2: The strategic defense management loop

2.0 APPROACH

2.1 Independent Cost Estimates

SAS-076 used the six major steps of Figure 3 to generate scientifically-sound cost estimates for multiple acquisition programs under consideration.

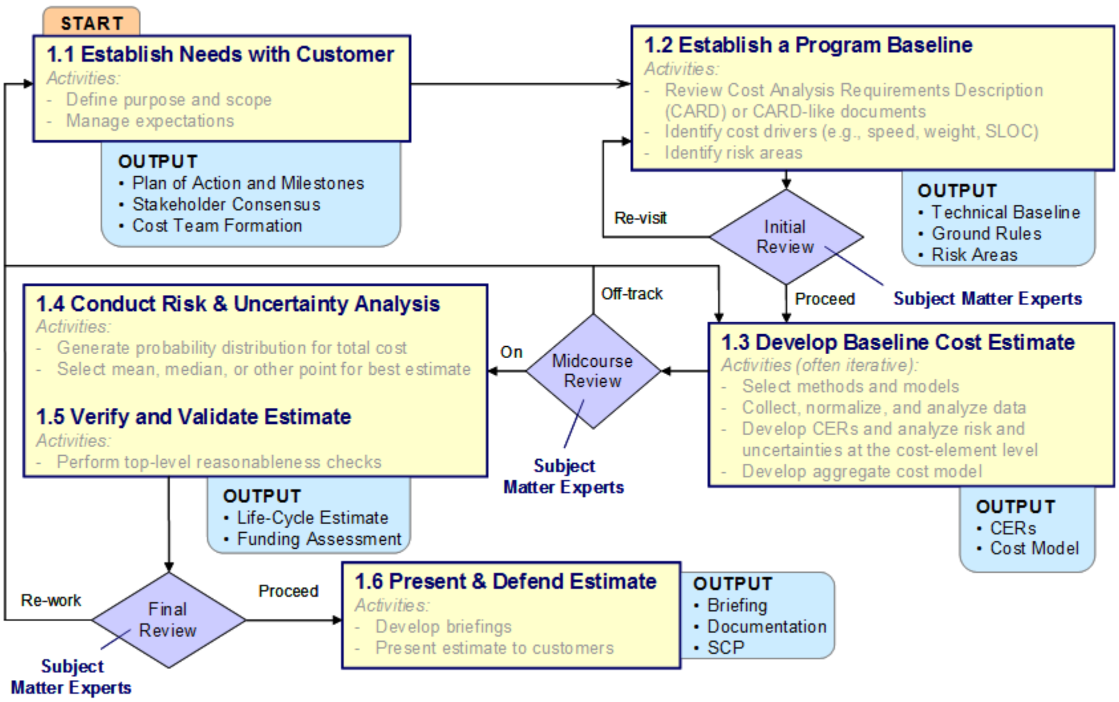

Figure 3: Methodology for the development of independent cost estimates

More specifically, for each program, SAS-076:

- Established Needs with the Customer.
  - Defined and managed expectations among stakeholders on cost-analysis activities, events and products throughout the life of the estimate.
- Established a Program Baseline.
  - Defined the program to include all technical and programmatic information required to generate the cost estimate.
- Developed the Baseline Cost Estimate.
  - Generated an estimate by collecting data, selecting methods, building models, and analyzing risks and uncertainties.
- Conducted Risk and Uncertainty Analysis.

  - Used an acceptable statistical technique to develop a probability distribution for the estimate.
- Verified and Validated the Cost Estimate.
  - Assessed critically the inputs, outputs, and methodology of the cost estimate using peer reviews and cross-checks.
- Presented and Defended the Estimate.
  - Finished documenting the estimate to produce an audit trail of source data, methods, and results, and present the estimate to principal decision makers in a cogent, understandable, and informative fashion.

Since a "second set of eyes" is of paramount importance in the discipline of defense cost analysis, subject matter experts provided guidance and feedback at critical review points.

2.2 Role of Life-Cycle Cost Analysis in Managing the Defense Enterprise

SAS-076 developed the following templates to ensure a common denominator of responses from NATO and PfP nations:

- Strategic Framework
  - Captures national practices in defining, managing, and implementing national security strategy
- Needs and Solutions
  - Defines the process for identifying military needs and developing and acquiring solutions
- Lexicon and Taxonomy
  - Captures national definitions of "defense capability" and defines methods that might be employed in grouping capabilities
- Role of Life-Cycle Cost Analysis
  - Captures the degree to which life-cycle cost analysis plays a role in planning, acquisition, and budgeting processes in each nation.

3.0 SUMMARY OF RESULTS

3.1 ICE on NATO Alliance Ground Surveillance System (AGS)

The SAS-076 Task Group focused its work on generating an independent cost estimate (ICE) on the acquisition phase of the program. This phase represents over 80% of the cost of the contract to be awarded to Northrop Grumman. The ICE, in turn, was based on:

- Historical costs of Global Hawk production (Blocks 30 and 40),
- An analogy for the new radar (Multi-Platform Radar Technology Improvement Program), based on the AESA radar on the F/A-18 E/F aircraft,

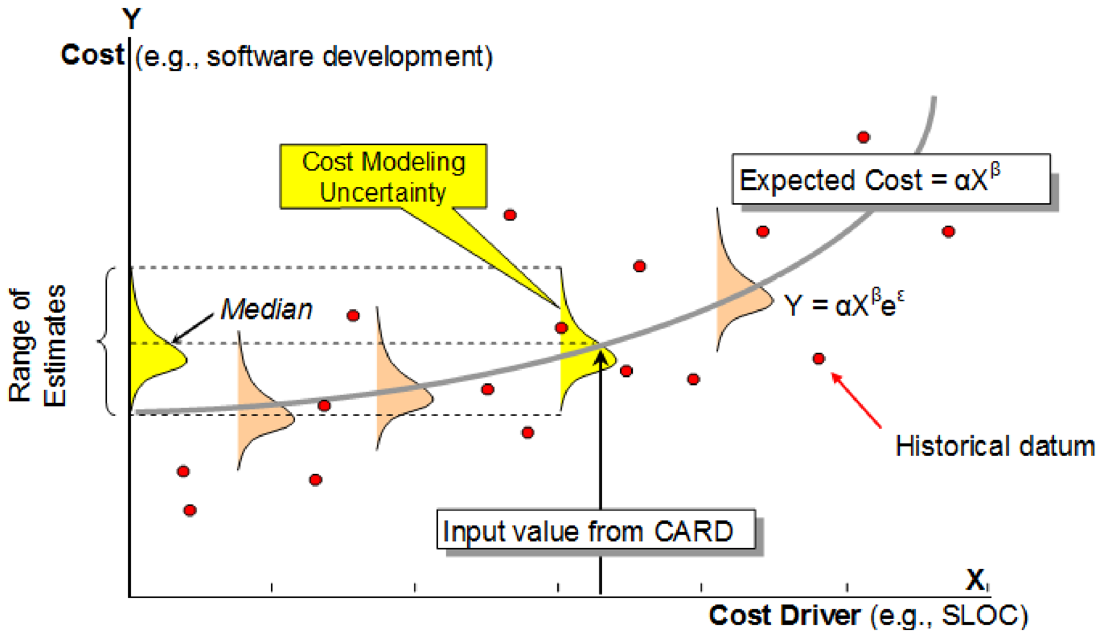

Figure 4: Estimating the cost for software development (example)

- Cost Estimating Relationships (CERs) for software development, as illustrated in Figure 4.

Operating and support costs for the in-service portion of the program were not formally proffered although one national participant in the group did some rough-order-of-magnitude estimates.

The Task Group conducted risk and uncertainty analysis for the acquisition program using benchmark coefficients of variation (CV) coupled with a point estimate to generate a cumulative probability distribution, or *S*-curve, as shown in Figure 5.

Results of the analysis were completely documented with the ICE delivered to the NATO AGS Management Agency (NAGSMA).

3.2 ICE on Royal Netherlands Navy LPDs

The full ICE was completed by estimating development and construction cost as an ex post exercise and O&S cost as an ex ante exercise. The SAS-076 Task Group used a novel application of known data mining algorithms to the problem of estimating the cost of development and construction for the Netherlands' LPDs. In a blind, ex post exercise, the Task Group set out to estimate the costs of these vessels and to then compare the estimates to actual costs (the Netherlands Royal Navy withheld the actual ship costs until the exercise was completed).

3.2.1 Acquisition ICE

Technical and cost data for ships similar to the HMS Rotterdam LPD was gathered. A database of 59 ships in 18 classes from 7 nations was compiled, spanning years (commissioned) from 1954 to 2010. For each ship, over a hundred descriptive and technical ship attributes were obtained, encompassing dimensions, performance, power generation, lift capacity, armament & countermeasures, sensors, combat & weapon control systems, etc.

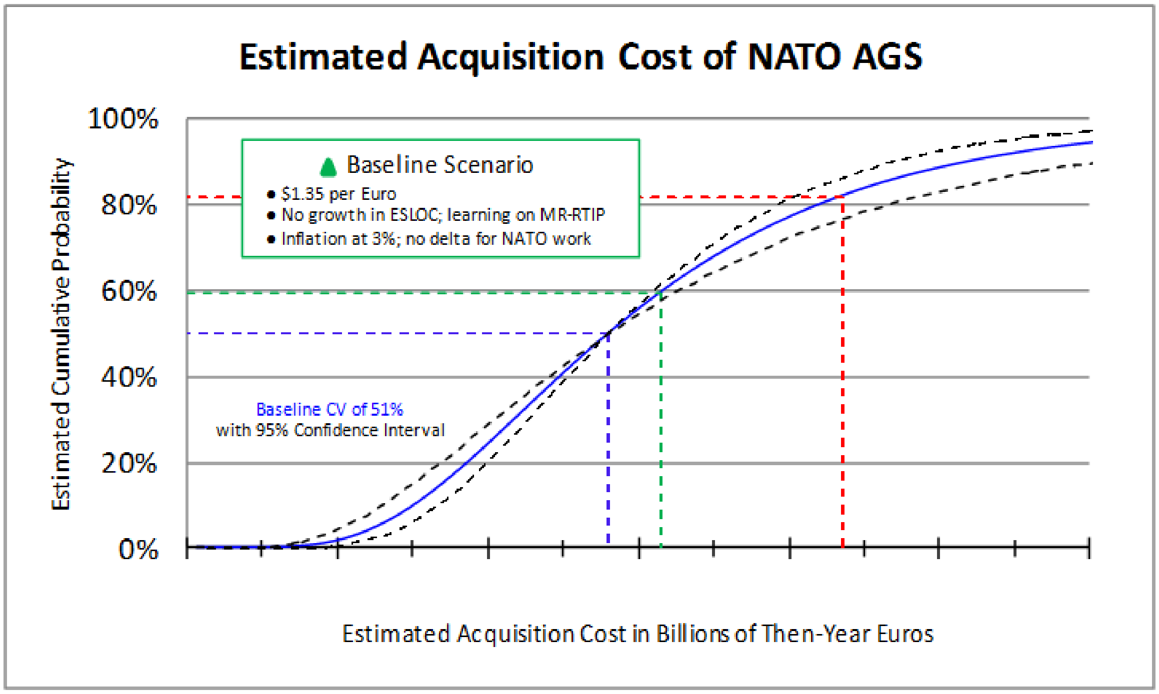

Figure 5: Estimated acquisition cost of NATO AGS

Ship development and production cost data was expressed in various currencies and a normalization procedure was required. Two cost estimating approaches were taken: parametric analysis and costing by analogy.

Parametric approach

Traditional ship building cost estimating relationships (CERs) are often mathematically simple or involve linear regression analysis (of historical systems or subsystems) on a single parameter. This is often insufficient - other cost driving factors must be incorporated to develop estimates of sufficient quality at the preliminary design phase. A parametric approach for ship cost estimation that incorporates a multitude of cost driving factors, while remaining a top-down approach applicable in early design phases of the procurement cycle was used. The M5 Model Tree Algorithm combines features of decision trees with linear regression models to both classify similar ships and build piece-wise multivariate linear regression models. Figure 6 depicts the M5 model tree applied to the NATO RTO SAS 076 ship data set.

Costing by Analogy

Cost estimation by analogy is typically accomplished by forecasting the cost of a new system based on the historical cost of similar or analogous system. There must be a reasonable correlation between the new and historical system. Subjectively chosen complexity factors are often used to adjust the analogous system's cost to produce an estimate. The credibility of the estimate for the new system may be undermined if the adjustment factors are not substantiated - this is a key disadvantage of the traditional analogy method. Hierarchical cluster analysis was used for a novel cost estimation by analogy approach void of the subjectivity inherent (of the tra-

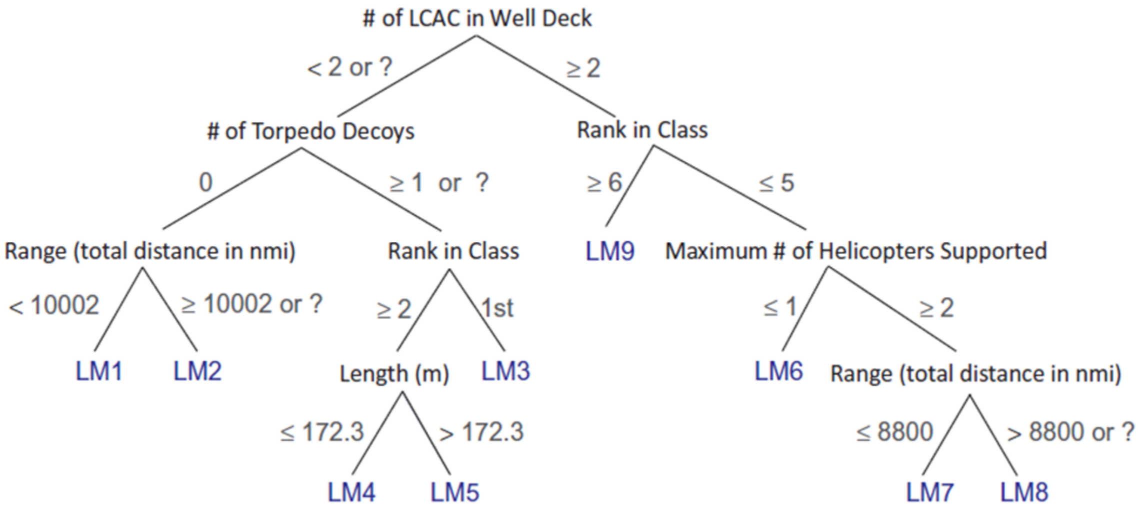

Figure 6: M5 model tree applied to the NATO RTO SAS 076 ship data set

ditional approach) in quantifying the cost of the technical and other differences between the historical system and the new system. The approach also considers multiple analogous systems rather than just one. Figure 7 illustrating the arrangement of the clusters produced by the hierarchical clustering of ships.

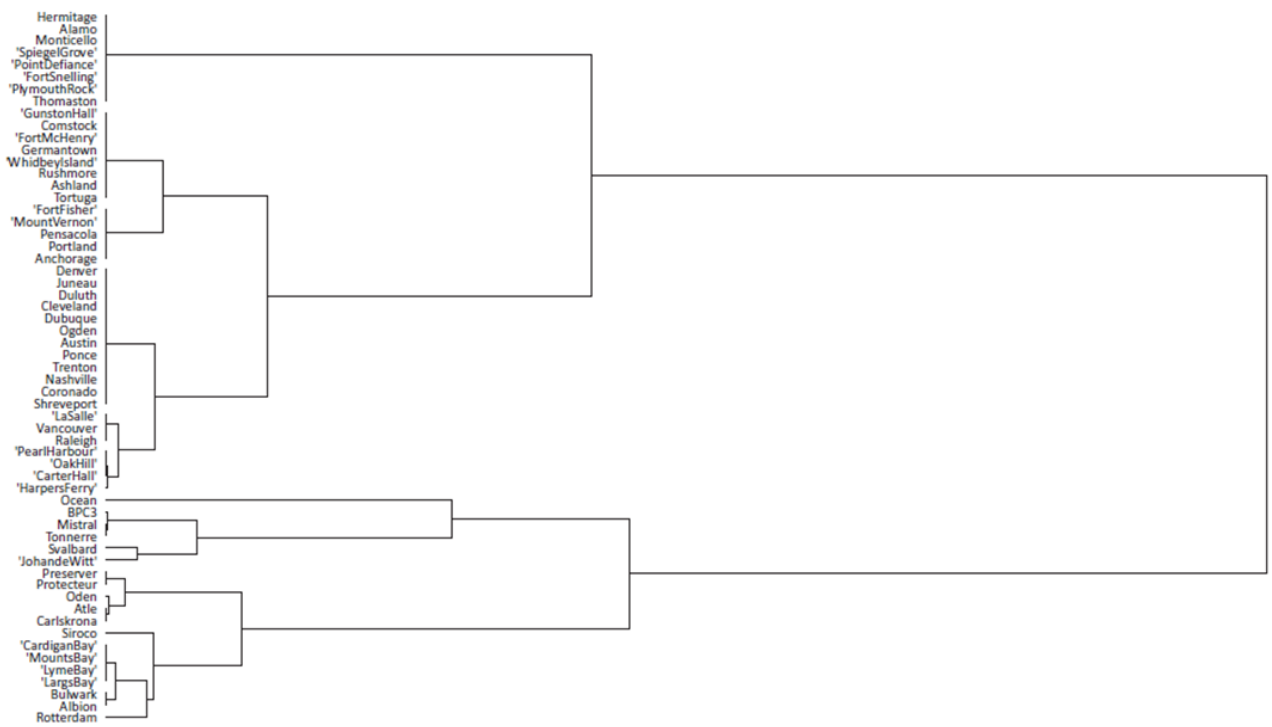

Figure 7: Dendrogram illustrating the arrangement of the clusters produced by the hierarchical clustering of ships

Results

The Royal Netherlands Navy revealed the actual development and production costs of HMS Rotterdam and Johan de Witt LPDs to the Task Group once the cost estimates were established. Figures 8 and 9 illustrate where the actual costs (thick vertical lines) fall with respect to the log-normal probability density and cumulative distribution functions for the M5 model tree and hierarchical cluster cost estimates for HMS Rotterdam LPD and Johan de Witt LPD (cost figures normalized to a fictitious notional common currency).

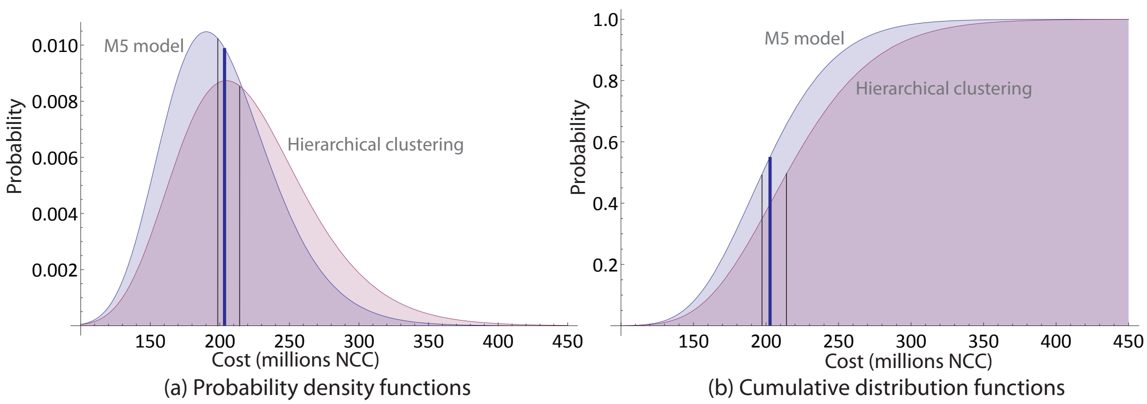

Figure 8: Probability density function (a) and cumulative distribution function (b) of the M5 model tree (blue) and hierarchical clustering (red) estimates of HMS Rotterdam LPD cost

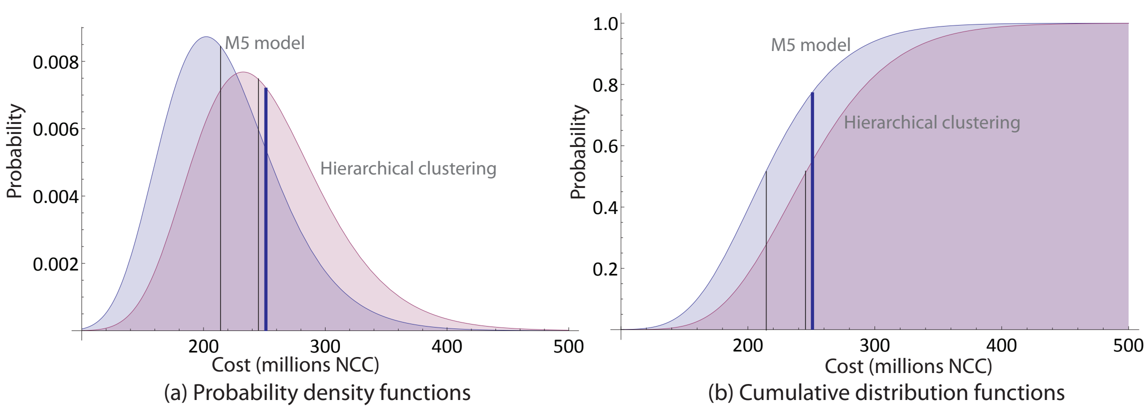

Figure 9: Probability density function (a) and cumulative distribution function (b) of the M5 model tree (blue) and hierarchical clustering (red) estimates of HMS Johan de Witt LPD cost

3.2.2 Operational & Support ICE

The ICE for operational & support (O&S) costs of the HMS Rotterdam LPD ship was an ex-ante exercise based on real organizational, operational, technical, and economic data gathered from the Royal Netherlands Navy (RNLN).

Methods

The ICE was based on three methods: parametric, analogy and engineering "bottom-up" methods. The parametric and analogy methods were applied by experts from the United States Naval Centre for Cost Analysis (NCCA) and were based on U.S. ship data pulled from the U.S. Naval Visibility and Management of Operating and Support Costs (VAMOSC) management information system. These methods were applied on the U.S. Department of Defense defined Cost Analysis Improvement Group (CAIG) Cost Breakdown Structure (CBS). The SAS-076 task group applied the engineering, bottom-up method using data from the RNLN and the CBS recommended in SAS-054. The most important reason for applying this detailed method is that it highlights the critical elements of the Rotterdam LPD and the logistical organization and that it shows the economical consequences of the technical system characteristics over time, allowing to evaluate the implication in costs for possible system solutions.

Results

Besides the effort performed by NCCA based on the VAMOSC data, SAS-076 managed to produce an estimate for the O&S costs based on the planned operational profile. The data provided by the RNLN, however, was not sufficient to produce a reliable cost estimate. Nevertheless, using open source data SAS-076 was able to produce an estimate for the O&S costs. Dividing the HMS Rotterdam ship's life cycle cost into acquisition (development and production) costs and O&S costs, SAS-076 estimated that cost of 0&S over 30 years of service represents 84% of the total life cycle cost.

3.3 Role of Life-Cycle Cost Analysis in Managing the Defense Enterprise

After an extensive literature review, the SAS-076 Task Group conducted a Capability Portfolio Analysis conference in Paris, France, in an effort to learn more about the application of the discipline in the international defense establishment. The group found that many existing models and processes within NATO fall short of the ideal goal of addressing all strategic requirements and the capabilities and costs of all components of the portfolio, large and small alike.

One exception was the Strategy-to-Tasks Model (STAM) of United States Special Operations Command (USSOCOM), headquartered at MacDill Air Force Base in Florida. USSOCOM is the combatant command for the worldwide use of Special Forces such as Navy Seals and Delta Operators. STAM does a good job of matching budget to strategy. And it uses impressive methodology in evaluating the warfighting value of assets in the USSOCOM portfolio. However, USSOCOM, unlike most ministries of defense within the Alliance, is not in the business of acquiring multi-billion dollar weapons systems since these are resourced through the Services in the U.S. DoD.

In a capability portfolio analysis pilot effort in the U.S., risk-reward bubble diagrams, such as shown in Figure 10, proved useful.

For the templates, the responses obtained from the sample of nations summarizes as below:

- Strategic Framework
  - All nations in the sample state general goals or ambitions in a national security document. Some nations offer more detail than others. All nations have processes and products that translate high-level objectives into more concrete policy parameters needed to build military forces. Most nations in the sample and many others within NATO engage in capability-based planning.
- Needs and Solutions

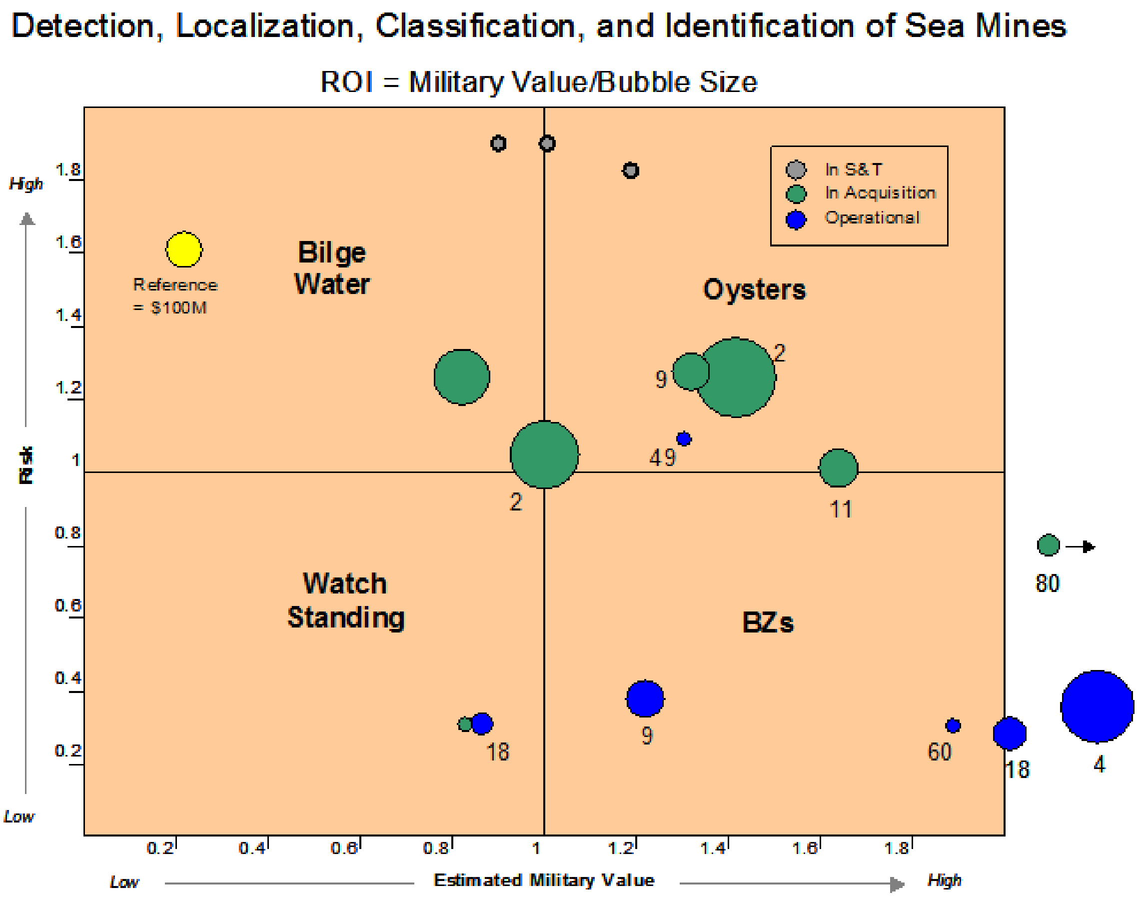

Figure 10: Risk-reward bubble diagram (example)

– Most of the sample nations described their process to identify needs. They all use capabilities as a part of defense planning and execute a gap analysis. All nations seem to have alternative solutions that in different ways are prioritized before any decisions for future acquisition are made. Scenarios are for identifying needs or for describing strategic frameworks or both. This also means that some scenarios are not as detailed as others. Due to different governmental organizations in each country the responsibility for working with needs and solutions differs between the nations.

- Lexicon and Taxonomy

  – Most nations from the sample seem to define capability in terms of ability to achieve a desired outcome. Regarding components of the capabilities there seems to be a significant commonality. The result of the template shows that some nations use a much more extensive structure than others.

- Role of Life-Cycle Cost Analysis

  – Of the seven nations answering the template only one nation uses life-cycle costing both for identifying defense needs, for defense programming and budgeting and for acquisition of materiel solutions. The best commonality is identified in the field of acquisition of materiel solutions.

Figure 11 provides a high-level summary of the SAS-076 analysis. As indicated by the legend in Figure 11, colours are used to evaluate the degree of use and role played played by life-cycle cost analysis during the various stages of defence planning and acquisition. Green indicates that life-cycle cost analysis is usually performed and plays a role in decision making. Red indicates the opposite—life-cycle costing does not play a role.

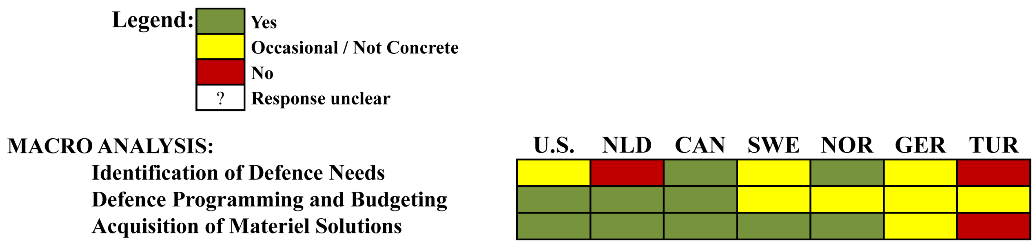

Figure 11: Macro analysis of role of life-cycle cost analysis in defence planning.

4.0 LESSONS IDENTIFIED

The goal of this effort was to apply the guideline that was developed by SAS-054 in multi-national programs, to gather lessons learned related to the guideline and, if necessary, to adapt or enhance the guideline. In Section 4.1 main lessons identified per each of the six main steps in generating an ICE (as per Figure 3) are specified with a detailed SAS-076 experience. Section 4.2 presents other, more generalized, ICE lessons identified that enhance the findings of SAS-054. Section 4.3 presents lessons learned from the SAS-076 capability portfolio analysis study.

4.1 Main ICE Lessons and Related SAS-076 Experience

4.1.1 Establishing Needs with Customers

Lessons Identified: Obtain stakeholder buy-in early on, generate an ICE development plan, and obtain key signatures

Example SAS-076 Experience: It is essential to obtain consensus if not unanimity on objectives and scope of the cost estimate. On NATO AGS, key discussions were required with major players to obtain permission to generate an ICE on the program, to obtain cooperation throughout the estimating process, and to publish results. An ICE development plan was generated to foster common understanding and to document agreements.

4.1.2 Establishing a Program Baseline

Lesson Identified: While the aim and the objective of the study are fundamental for the way the cost analysis is conducted, cost analysts should be flexible and anticipate changes to the cost boundary during the cost estimating process.

Example SAS-076 Experience: The cost boundary changed during the cost estimating process of the O&S costs of the Netherlands' LPDs: helicopters were at first not included but additional informations from the

RNLN required a change. Similarly, originally the disposal costs were included in the Cost Breakdown Structure, but the RNLN could not provide a strategy for the disposal of the ships and this caused the removal of these costs from the Cost Breakdown Structure.

4.1.3 Developing Baseline Cost Estimates

Lesson Identified: Don't limit the scope of historical data to use and be open to new costing methods.

Example SAS-076 Experience: When SAS-076 gathered data for ships similar to the Netherlands LPD's (for the acquisition ICE) the group did not limit themselves to ships very close to the Netherlands' LPDs. For example, civilian ships like icebreakers were also included because data related to these ships could have relevant information (e.g., same size/different function and different size/same function). Similarly, for each ship a plethora of technical and performance characteristics where gathered. In some cases data was unobtainable, but rather than discarding such ships, methodologies were proposed that could handle missing values. The data available determined, in a large extent, the choice of methods. It was a continuous interaction between choices of methods and computer models and availability of data. The new methodology used, based on data mining, is very valuable as it requires only publicly available technical data of attributes and some cost data. On the other hand the complexity of the analogy method based on hierarchical clustering lead to computational difficulties when using over one hundred attributes per ship. This issue was dealt with by applying principal component analysis and reducing the dimensionality of the input without significant loss of information.

4.1.4 Conducting Risk and Uncertainty Analysis

Lesson Identified: When possible, use multiple techniques for risk and uncertainty analysis.

Example SAS-076 Experience: The use of historical CVs within the context of scenario-based analysis is easier and more complete than traditional Monte Carlo simulation. All elements of risk and captured, and considerable time saved, by employing benchmark CVs. Use of more than one technique may be in order, and a best practice. For example, AGS risks might be first estimated using Monte Carlo simulation, with benchmark CVs then serving as an independent validation check on results.

4.1.5 Verifying and Validating Estimates

Lesson Identified: Scrutinize initial cost model outputs in detail and if necessary determine whether to change the model or adjust results before considering omitting historical data.

Example SAS-076 Experience: A closer look at the Netherlands LPD acquisition CER showed that the individual linear regression models were mostly intuitive: the cost of a ship increases as the length or the number of landing craft supported or number of torpedo decoy systems increase(s). The regression models also predict a shipbuilding learning curve as the cost of constructing a ship decreases as a function of the ship's rank in class. However, the negative coefficient for a ship's range (sailing time) in the regression models was counter-intuitive. It seemed unlikely that a ship would cost less if its range was increased. A closer look at the SAS-076 ship data explained the anomaly: a small subset of the ships had a combination of low cost and outlying sailing time ranges. Adjusting the regression models (by disabling the particular sailing time attribute) offered no guarantee that the regenerated model would not substitute this attribute with another also allocated a negative coefficient. Similarly, removing certain ships from the data set provided no guarantees. Rather than subjectively diminishing the data set, SAS-076 noted the anomaly and discussing them as part of the results. As a post analysis SAS-076 substituted the Johan de Witt sailing range (also an outlier) with the median sailing range of the SAS-076 ship data set, effectively neutralizing the attribute. This resulted in a revised estimate which turned out to be within 1% of the actual cost.

4.1.6 Presenting and Defending Estimates

Lesson Identified: It is best to start documenting the cost estimate as it is developed. Trying to recapture rationale, judgments, and the details of intricate statistical analyses after the fact is, at best, extremely difficult and time consuming.

Example SAS-076 Experience: Due to the nature of the SAS-076 task group, which met 3-4 times a year for three years, it was necessary to compile presentations on methodologies, assumptions, and results in preparation for each meeting in order to facilitate discussion and progress. A turnover in participants over the years also forced the group to regularly document its findings in order not to lose any information. Although hindered by the discontinuous nature of the meetings (naturally SAS-076 participants had national obligations to attend to between meetings), the regular updating of models and presentations facilitated report documentation and offered a trace of the decisions made at various stages.

4.2 Other ICE Lessons

- A sound, robust life-cycle cost estimate is based on a well-defined program. Accuracy and completeness of the definition are critical in producing an estimate that informs rather than confuses decisions on the allocation of scare resources within NATO and PfP nations. The better the definition, ceteris paribus, the higher will be the quality, flexibility, and usability of the cost estimate.
- An ambiguously defined program increases the use of assumptions, drives up estimation risk, and shifts the burden of uncertainty to senior decision makers.
- Defining the program is not a one-step-and-stop activity. It's common to refine the definition of the program throughout the estimation process.
- Life cycle costing is a data driven process, as the amount, quality and other characteristics of the available data often define what methods and models can be applied, what analyses can be performed, and hence, the results that can be achieved.
- Robust life-cycle cost analysis requires the collection of metadata from myriad sources.
- There are a wide variety of methods and models available for conducting risk and uncertainty analysis of life-cycle cost estimates of defense acquisition programs. Each, if used properly, can yield scientifically sound results. That said, there's simply no substitute for taking the time and effort to understand the technical risks and challenges in developing and producing sophisticated defense systems.
- It's essential to convey to senior leadership the notion that cost estimates are uncertain, that acquisition programs can and do incur difficulties, and that the probability of a cost estimate becoming reality, when expressed as a single number, is precisely zero.

- Since uncertainty and subjectivity are always present in the cost-estimating process, sound procedures for verification and validation are essential to ensure the delivery of quality products, and, importantly, to capture and store reliable metadata on the estimate for future use and continual process improvement.
- Use of meaningful, well-crafted visual displays is important in communicating the results of detailed cost analyses to stakeholders.
- A best practice is to start documenting the cost estimate as it is developed. Trying to recapture rationale, judgments, and the details of intricate statistical analyses after the fact is, at best, extremely difficult and time consuming.
- Since the precise distribution of the cost estimate is never known with absolute certitude, it's perhaps helpful to provide context through the use of historical norms. An example would be comparing an estimated probability distribution for a current acquisition program to one based on the same point estimate (such as the median or mean) but using a variance based on sample CVs from analogous, historical programs.

4.3 Life Cycle Cost Analysis in Managing the Defense Enterprise

Based on responses from seven countries, and through a process of vigorous discussion and even heated debate, SAS-076 identified the following lessons learned with respect to the role played be cost analysis in managing the defence enterprise.

1. **Engage Early-On:** Use cost assessments to inform the strategic decision planning process on what a country can and cannot afford. Canada and Scandinavian countries seem the best practitioners on this score.
2. **Budget and Program to the Cost Estimate:** Independent cost estimates and cost assessments are valuable only to the degree they are used. A best practice is to generate an independent life-cycle cost estimate for every major weapon system acquisition program and to reflect this estimate in planning and budgeting systems.
3. **Make Cost the Denominator in Needs and Solutions Analysis:** In identifying military needs and solutions, capability-based planning is the gold standard in NATO today. A best practice, within the context of capability portfolio analysis as illustrated in Figure 10, is to compute a return on investment for defence assets defined as:

   $$\frac{\text{Military Value}}{\text{Life-Cycle Costs}}.$$

   It's important to note that risk and balance are other essential dimensions of a complete analysis.
4. **Move to the "Left" in Acquisition:** Many, if not all, countries extensively support the acquisition process at key decision points, called "gates" in the United Kingdom, milestones in the United States. However, many cost analysts object to providing cost estimates early in acquisition when systems are only vaguely defined and exist only in design. However, paradoxically, this is when the cost estimates are of the most importance. Much more extensive cost-analysis support needs to be provided in early design phases. Rough order of magnitude estimates a this point in the life cycle will help empower informed decisions on the allocation of scarce defence assets.

5. **Optimize from an Alliance Perspective:** Given pervasive threat to the security of NATO and its alliance members across the broad spectrum of conflict, optimization of military capability seems in order. Duplication of effort, such as several countries possessing extensive sea mine counter-measure capability, might be avoided. Individual Alliance members might develop expertise in a war-fighting domain that could be used to the benefit of the entire Alliance in times of conflict. Savings of hundreds of billions of Euros per annum might be achieved by managing from a NATO enterprise perspective.

6. **Present Decision Makers with Menu of Portfolios:** Senior defense decision makers express a strong demand for a *menu* of acquisition *alternatives* from which to choose. Heretofore, inordinate attention has been devoted, at high levels, to the management of *individual* acquisition programs. Attention to acquisition details, at high levels, might be better delegated to subordinate authorities in each military department or acquisition community. Senior decision makers, instead, would focus on a complete *set* or *portfolio* of systems in any war fighting or mission area. A review of current and alternative portfolios would shift attention of senior decision makers to where it rightfully belongs, to addressing the fundamental, multiple needs of a ministry of defense, and *trade-off space*, in the face of an entire *spectrum of threats*.

5.0 CONCLUSIONS

Working as a coherent team, the Task Group was successful in generating credible, complete, scientifically-sound independent cost estimates on:

- HMS Rotterdam and HMS Johan de Witt Landing Platform Docks (LPD) of the Netherlands; and
- NATO's Alliance Ground Surveillance System (AGS).

These conclusions are offered:

- It is, in fact, possible to generate an ICE on a major acquisition program using an international team of dedicated cost analysts.
- It is difficult, but not impossible, to share cost data across nations. Non-disclosure forms need to be completed, and information closely held. Further, it is useful if not essential to obtain buy-in early on from major stakeholders. For example, for AGS, the SAS-076 team generated an ICE development plan and obtained signatures from the Chairman of the Board of AGS Management Organization (NAGSMO), the Director the AGS Management Agency (NAGSMA), and the Director the SAS-076 study group.
- The SAS-054 guidelines on methods and models for cost analysis are, in fact, applicable in a cost estimating environment. The SAS-076 Task Group followed these guidelines extensively and recommends some enhancements,such as:
  - Differentiate between approaches and methods: parametric, analogy, and engineering methods can each be applied in a top-down or bottom-up approach.
  - The SAS-054 guidelines for cost normalization should be expanded to consider multi-national data sets where different currencies and base years are present. The approach taken by SAS-076 in this study can be used as an example.

  - Describe the new methods for acquisition costs developed by the group based on data mining techniques.

In the realm of managing the defense enterprise, the SAS-076 Task Group offers these conclusions:

- Portfolio analysis techniques can indeed be employed fruitfully in national defense.
- Major goals of portfolio analysis typically include maximizing value of individual projects, balancing investments, and adhering to strategy.
- No model, of course, is perfect. That is, models are parsimonious, plausible, and hopefully informative, but do not provide the ultimate truth.
- Provide senior decision makers a menu of investment portfolios from which to choose.
- Present joint solution space in all investment portfolios.
- Minimize subjectivity in assessing military value.
- Always assess capabilities, risk, and life-cycle costs of assets. All three dimensions are important, and leaving out costs will skew results.
- Newly developed methods in other areas than cost analysis should always be considered for application in the cost analysis area.

6.0 REFERENCES

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[2] Stephan Spiegeleire, "*Closing the Loop*," 2008, Hague Centre for Strategic Studies.

Annex A

Estimating the Acquisition Cost of the Alliance Ground Surveillance (AGS) System

NATO RTO Systems Analysis and Studies Task Group-076*

November 1, 2011

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1.0 INTRODUCTION

1.1 Historical Background

The concept for an all-weather military surveillance capability for NATO followed from Operation Desert Storm in Kuwait and Iraq, where in 1991 the U.S. successfully deployed the then developmental Joint Surveillance Target Attack Radar System (JSTARS). Unaffected by day/night or adverse weather conditions, JSTARS proved formidable in detecting and tracking enemy movements over vast terrain, while simultaneously disseminating near real-time data to U.S. and coalition forces.

In 1994, following a detailed operational assessment of NATO‘s military requirements, NATO formalized Alliance Ground Surveillance (AGS) as a Military Operational Requirement (MORS), and in 1995 the North Atlantic Council (NAC) formally validated the requirement for a NATO-owned and operated wide-area air-to-ground surveillance capability, known as the Alliance Ground Surveillance (AGS) system [1].

After years of exploring options for AGS that repeatedly saw the NATO nations unable to reach agreement towards a viable procurement programme; in September 2009, 15 of the 28 member nations[1] signed a Program Memorandum of Understanding (PMoU) to fund the developmental phase of a programme, overseen by the NATO Alliance Ground Surveillance Management Agency (NAGSMA) located in Brussels, Belgium.

1.2 AGS Core Overview

Figure 1 depicts the general principle of operation for the AGS wide-area ground surveillance system. The AGS core consists of a fully integrated system with an air segment, a ground segment and a support segment.

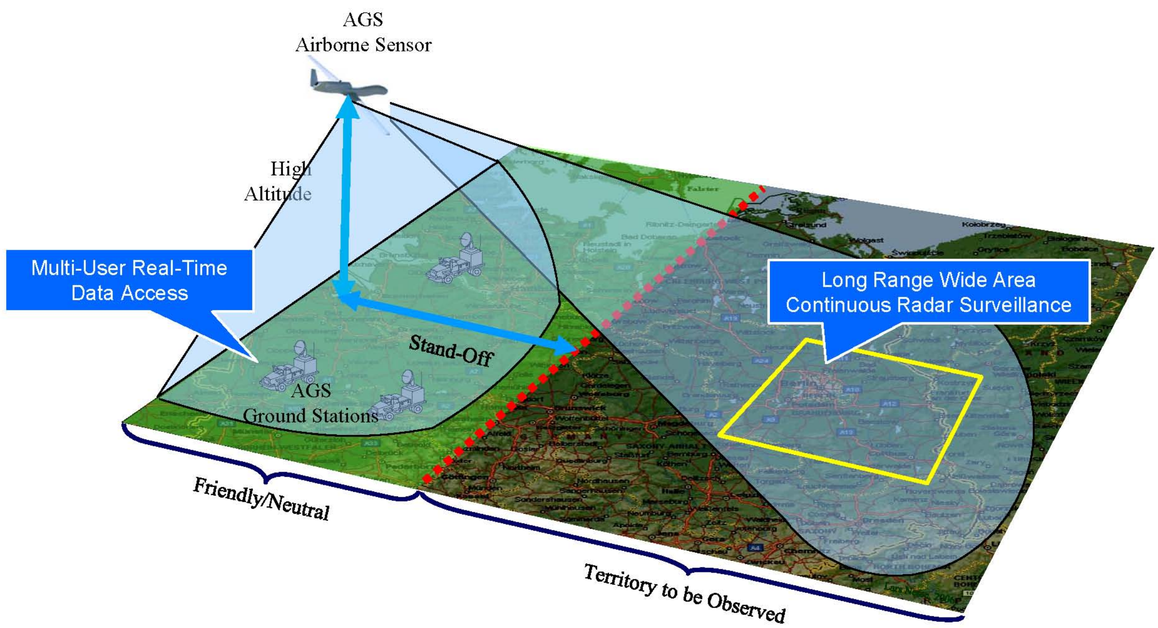


Figure 1: Principle of operation of the AGS core wide-area ground surveillance system

[1] In June 2010, Denmark formally withdrew from the program as part of a move to cut $500 million from planned defence spending between 2010-2014 [2]. The 14 remaining nations are: Bulgaria, Canada, the Czech Republic, Estonia, Germany, Italy, Latvia, Lithuania, Luxembourg, Norway, Romania, Slovakia, Slovenia, and the United States.

The air segment will be based on the Northrop Grumman RQ-4B Global Hawk Block 40[2] high-altitude[3], long endurance, unmanned aerial vehicle (UAV), equipped with advanced multi-platform radar technology insertion program (MP-RTIP) for wide-area surveillance. MP-RTIP uses active electronically scanned array radar to provide a near-real-time horizontally integrated view of the battlespace, capable of detecting and tracking moving objects throughout the observed territory and beyond line-of-sight, as well as providing radar imagery of target locations [3, 4]. Figure 2 depicts the main components of the system.

The ground segment will provide a direct interface between the AGS core system and a number of fixed and deployable Command, Control, Intelligence, Surveillance and Reconnaissance (C2ISR) systems for ISR data exploitation and external dissemination to multiple deployed and non-deployed operational users.

The deployable components consist of four shelter-based Transportable General Ground Stations (TGGS), 11 vehicle-based Mobile General Ground Stations (MGGS), and five Command & Control Units (UCE) that are each self-contained elements with communications and complete environmental control for a crew of two. Also included are 15 Mobile General Communications Stations (MGCS), which serve as the mobile communication component for the MGGS. In that sense, each deployable ground station must be fully functional with low probability of being inoperative, be able to support NATO operations on a continuous basis, and being able to provide a fully integrated capability to each user without having to rely on external infrastructure [1].

The non-deployable component provides a centralized ISR service for high-performance processing at a Main Operating Base (MOB), currently located at Sigonella Air Base, Italy. This Main Operating Station (MOS) will be operate continuously in support of missions, training and maintenance; and will maintain the same data link connectivity with the AGS air platform as the deployable ground stations albeit through a satellite communication (SATCOM) link since the MOS will most certainly be beyond line-of-sight range from the operational theatre [1].

The support elements will support users from operative to tactical levels, and consist of UAV flight trainers, operator trainers and remote work stations. Also included are Peculiar Support Equipment (PSE) which will consist of a set of specialized tools for maintenance and repair of the MGGS and the MGCC in the field [5].

Figure 2: Elements of the NATO AGS system

[2] Variants of Global Hawk aircraft are described by reference to 'Block' numbers, e.g., Block 10, Block 20, Block 30, etc.

[3] In submitting its bid, Northrop Grumman has built its program around six MP-RTIP equipped Block 40 Global Hawks [2]. Nevertheless, NAGSMA questions the bid and remains committed to a program consisting of eight Unmanned Aerial Vehicles (UAVs).

1.3 Study Objective

The objective of this report is to present the ICE for the NATO AGS team based on NATO Research & Technology Organization (RTO) System Analysis and Studies (SAS) task group (SAS-054) guidelines for best practice. Since this is a new acquisition with contract expected to be awarded in 2011 and AGS operational by 2014, this ICE focuses exclusively on development and production costs only.

1.4 Scope

Per demand from the NATO AGS Management Agency (NAGSMA), the SAS-076 Task Group focused its work on generating an independent cost estimate (ICE) on the acquisition phase of the program. This phase represents over 80% of the cost of the contract to be awarded to Northrop Grumman.

The ICE, in turn, was based on:

- Historical costs of Global Hawk production (Blocks 30 and 40),
- An analogy for the new radar (Multi-Platform Radar Technology Improvement Program), based on the AESA radar on the F/A-18 E/F aircraft,
- Cost Estimating Relationships (CERs) for software development.

Operating and support costs for the in-service portion of the program were not formally proffered although one national participant in the group did some rough-order-of-magnitude estimates.

The Task Group conducted risk and uncertainty analysis for the acquisition program using benchmark coefficients of variation (CV) coupled with a point estimate to generate a cumulative probability distribution, or S-curve.

Results of the analysis were completely documented with the ICE delivered to NAGSMA.

1.5 Outline

After a detailed introduction into the AGS system (including the historical background and core overview), and the objectives for SAS 076 as they apply to the NATO AGS portion of task group,

Section 2 presents the AGS program baseline including the detailed cost breakdown structure. The entire report is structured along the lines of the AGS program baseline (see Figure 3), where the main cost drivers are first specified, followed by the detailed cost estimates for each component described by the cost breakdown structure, and finally concluding the study with the risk and uncertainty analysis. In this sense, a logical step-by-step approach was taken that could be applied to future programs of this nature.

Section 3 presents the main financial aspects of the study, including inflation rates, definitions for *constant year* and *then year* dollars, and the conversions from *Raw Aircraft Procurement* to *Weighted Aircraft Procurement*. Section 3 concludes with a discussion on foreign exchange rates and the forecasted USD/Euro exchange rate out to January 2015.

Section 4 is the main analysis portion of the study. In this section detailed cost modelling is performed on all system components based on the cost breakdown structure of Table 1. For most components where actual costs existed, learning curves were established from the U.S. Global Hawk RQ-4 production line. In other cases where statistical significance of the regression components was lacking, mean values of the Lot 4, 5 and 6 unit costs defined the mean unit cost of the component.

Section 5 concludes the analysis portion of the report with a detailed risk and uncertainty analysis using the Enhanced Scenario-Based Method (eSBM) for the major risk elements of this study under three scenarios: “Baseline” (Most likely to occur), “Pessimistic”, and “Resource Constrained”.

Section 6 provides a conclusion to the report with a point discussion on the main limitations for the study.

2.0 THE AGS PROGRAM BASELINE

Developing an ICE for a major acquisition programme consists of a number of steps, with checks and balances established at each milestone. Figure 3 presents a five-step program which could be used for any life cycle cost estimate where, at each step, activities are defined and outputs are realized. Some steps could be completed within a few months, e.g., *Establish Needs with Customer*, whereas others could take years, e.g., *1.3 Develop Cost Estimate*, where issues with gathering and validating data of un-fielded systems, or developing an uncertainty profile far into the future, hamper the development of a viable cost estimate.

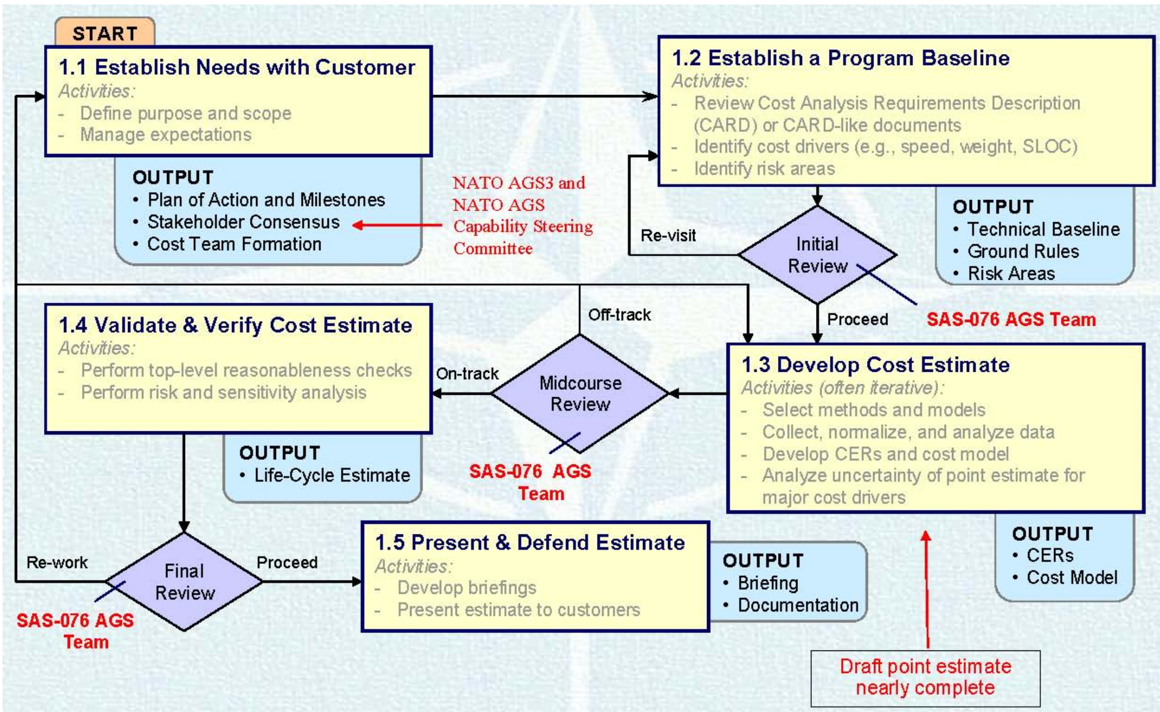


Figure 3: Methodology for the NATO AGS independent cost estimate

2.1 General Assumptions

The AGS cost team estimated the program of record, as defined by the NATO AGS Management Agency, as it evolved over the course of the study. As requested by NAGSMA, costs were estimated in both constant and then-year dollars and Euros.

2.2 The Cost Breakdown Structure (CBS)

The NATO AGS ICE used a product oriented breakdown structure according to the data available, which was fairly limited considering that the system is still in development. The cost breakdown structure that the team developed consists of 12 elements that define the cost drivers for the NATO AGS system. These can be seen listed in Table 1.

Table 1: The cost breakdown structure for NATO AGS

WBS #	Cost Element	WBS #	Cost Element
1	**NATO AGS UAV System**	1.3	**Ground/Support Segment**
1.1	**Air Vehicle**	1.3.1	**Hardware**
1.1.1	**Airframe**	1.3.1.1	Main Operating Station (MOS)
1.1.1.1	Wing	1.3.1.2	Mobile General Ground Stations (MGGS)
1.1.1.2	Fuselage	1.3.1.3	Mobile General Communications Stations (MGCS)
1.1.1.3	Empennage	1.3.1.4	Transportable General Ground Stations (TGGS)
1.1.1.4	Subsystems	1.3.1.5	UAV Command and Control Elements
1.1.1.4.1	Nacelle	1.3.1.6	Remote Workstations
1.1.1.4.2	Fairings	1.3.1.7	UAV Flight Trainers
1.1.1.4.3	Landing Gear + "Other"	1.3.1.8	Ground Station Test & Integration
1.1.2	**Propulsion**	1.3.2	**Software Development**
1.1.3	**Communications**	1.3.2.1	Air Vehicle/Payload
1.1.3.1	DataLinks Link 16 included here? Or under payload?	1.3.2.2	Mission Operations Support
1.1.3.2	Satellite Communications	1.3.2.3	Transportable General Ground Stations
1.1.3.2.1	Ku Satellite Radio	1.3.2.4	Mobile General Ground Stations
1.1.3.2.2	Satellite Communications (SATCOM) Voice	1.3.2.5	Mobile General Communications Stations
1.1.3.2.3	International Maritime SATCOM	1.3.2.6	CSOP
1.1.3.3	UHF/VHF Communications	1.3.2.7	UAV Command and Control Elements
1.1.3.3.1	UHF/VHF Radios	1.3.2.8	System Test & Integration
1.1.3.3.2	UHF Demand Assigned Multiple Access (DAMA) SATCOM	1.4	**Systems Engineering/Program Management**
1.1.4	**Navigation/Guidance**	1.4.1	**Systems Engineering (SE)**
1.1.4.1	(2) Global Positioning Systems	1.4.2	**Program Management (PM)**
1.1.4.2	OmniStar Differential Global Positioning System (DGPS)	1.5	**Systems Test & Evaluation**
1.1.4.3	IFF Transponder/ Traffic Alert Collision (TCAS-II)	1.6	**Training**
1.1.4.4	Worldwide Operations Hardware Suite	1.7	**Data**
1.1.5	**Central Computer**	1.8	**Peculiar Support Equipment**
1.1.6	**Auxiliary Equipment**	1.9	**Common Support Equipment**
1.1.7	**Integration, Assembly, Test Checkout**	1.1	**Operational/Site Activation**
1.2	**Payloads**	1.11	**Industrial Facilities**
1.2.1	**Reconnaissance**	1.12	**Initial Spares and Repair Parts**
1.2.1.3	MP-RTIP		
1.2.2	**NATO AGS Unique**	Add-on	General and Administrative
1.2.2.1	Electronic Support Measures (ESM)		Facilities Capital Cost of Money
1.2.2.2	Radar Warning Receiver (RWR)		Profit
1.2.2.3	IFF Interrogator		
1.2.6	**Payloads Integration Assembly and Checkout**		

2.2.1 The Air Vehicle Segment

The air vehicle segment is comprised of:

1. Eight “Off-the-shelf” (OTS) RQ-4B Global Hawk Block 40 UAVs made up of an airframe, i.e., wings, fuselage, empennage, landing gear and subsystems, its propulsion system and navigation/guidance systems;
2. An OTS Ku-band SATCOM package for the transmission of high volumes of data to multiple users within a large area;
3. A wide-band line-of-sight datalink package capable of simultaneous broadcast and directional operation [1];
4. A Link 16 datalink package intended for use in the transmission of highly filtered data to external users;
5. VHF/UHF Saturn radio communications for integration within European Airspace;
6. OmniSTAR wide-area differential global positioning system (DGPS) using satellite broadcast techniques;
7. Identification Friend or Foe (IFF) interrogator.

2.2.2 The Payload Segment

The payload segment is comprised of:

1. Northrop Grumman/Raytheon's new MP-RTIP active electronically scanned array (AESA) technology for long range, very high-resolution, simultaneous synthetic aperture radar (SAR) and ground moving target indicator (GMTI) capabilities;

2. Electronic Intelligence (ELINT) sensors including emitter detection and identification through Electronic Support Measures (ESM) and Radar Warning Receivers (RWR).

2.2.3 The Ground/Support Segment

The ground/support segment comprises two areas for costing: one for hardware and another for software development. The hardware components have already been discussed in detail in section 1.2 and consist of:

1. 5 OTS Command & Control Units (Unit Control Elements);

2. 11 Mobile General Ground Stations (MGGS);

3. 16 Mobile General Communications Stations (MGCS);

4. 4 Transportable General Ground Stations (TGGS);

5. 22 Remote Workstations;

6. OTS UAV Flight Trainers;

7. Deployable Operator Trainers.

Software is a vital part of the air and ground segments and its level of complexity is usually expressed in terms of operational environment and application domain. For the operational environment, software drives the avionics for the air platform including control, monitoring, communication and navigation. Also, ground-based mission critical software for fixed and mobile sites all lie within the operational environment [6].

Within the application domain, complex software algorithms are required for signal processing of large volumes of data from command, control and communications systems. Included in this domain is software used for the development, testing and support of applications including trainer software.

Software development for both domains consists of Equivalent Source Lines of Code (ESLOC) that is typically used to predict the amount of programming that will be required in the development effort, as well as to estimate programming productivity or maintainability once the software is produced.

2.2.4 Miscellaneous Support Elements 1.4 – 1.12

The remaining cost elements from Systems Engineering/Program Management (1.4) to Initial Spares and Repair Parts (1.12) provide support to the main systems and subsystems. Each element's cost is based on a percentage of the total estimated cost for the $\text{AirVehicle} + \text{Payload} + \text{GroundSegment}$.

3.0 FINANCIAL CONSIDERATIONS

Prior to developing the AGS cost estimate, we need to develop cost models that reflect all prior year, current and future costs at the level of prices of a base year, which in our case is 2010. Termed *constant year (CY) dollars*, they capture the time value of money by adjusting through compounding and discounting cash flows to reflect the increased value of money.

Costs in *then year (TY) dollars*[4] reflect the purchasing power of the dollar in the year the costs are incurred. Prior year costs given in then year dollars are the actual costs incurred in those years. Future year costs are the projected values that will be paid out in future years.

3.1 Inflation

Inflation rates for AGS design, development, and production will likely differ from values recently experienced in the aerospace industries in the United States, Canada, and Europe. The ICE team is using a baseline value of 3% inflation per annum for outyear projections, weighted according to the relative contributions of the 14 NATO countries participating in the program. However, inflation as measured by the consumer price index seems to be accelerating in Europe as the economic recovery gains traction[5]. Defense inflation generally runs higher than economy-wide figures by perhaps 100 to 300 basis points per year, but follows the same trend. An uptick in rates is a risk in the next few years.

3.2 Raw Aircraft Procurement

Table 2 lists the U.S. constant year dollars relative to the base year 2010. For the raw aircraft procurement numbers from FY 2002 – FY 2010, the discounted present value (PV) costs in 2010 dollars are determined by

$$\mathrm{PV} = \sum_{t=0}^{t=8} \frac{\mathrm{FV}_{Base}}{(1+r)^t} , \tag{1}$$

where $\mathrm{FV}_{\mathrm{Base}}$ is the future cash flow in the base year 2010, r is the average inflation rate of 3% per annum for the U.S., Canada and Europe, and the sum is over the 9-year period from FY 2010 ($t = 0$) to FY 2002 ($t = 8$).

For the raw aircraft procurement (RAP) numbers from FY 2010 – FY 2020, relative to the base year, the future value (FV) of the cash flow is obtained by

$$\mathrm{FV} = \sum_{t=0}^{t=10} \mathrm{PV}_{\mathrm{Base}} (1+r)^t , \tag{2}$$

where FV is now the future cash flow relative to the constant base year 2010, and the sum is over the 11-year period from FY 2010 ($t = 0$) to FY 2020 ($t = 10$).

3.3 Weighted Aircraft Procurement

The above calculations are simply a prerequisite to determining the estimated TY to CY dollar conversions for U.S. procurement costs of NATO AGS. In the U.S., Total Obligational Authority (TOA) funding is the most accurate reflection of program spending. It is the amount of money received in a fiscal year (01 October to

[4] U.S. terminology. In Canada, TY dollars are referred to as budget year (BY) dollars.

[5] Euro area annual inflation was 2.7% in March 2011, up from 2.4% in February. A year earlier the rate was 1.6% [7].

Table 2: U.S. constant year dollars (base year highlighted)

	FY02[a]	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14
Raw Aircraft Procurement	0.789	0.813	0.837	0.863	0.888	0.915	0.943	0.971	1.000	1.030	1.061	1.093	1.126
Weighted Aircraft Procurement	0.824	0.849	0.874	0.901	0.928	0.955	0.984	1.014	1.044	1.075	1.108	1.141	1.175

[a]01 October 2001 to 31 September 2002

31 September) from Congress to spend on defense programs. The spending profile (outlays) we use for NATO AGS is based on the time span of U.S. Navy aircraft procurement outlays of 15%, 40%, 28.6%, 10%, 4.5%, and 1.9% of TOA funding in each buy year. In our case, we use a four year outlay profile and truncate the spending to 15%, 40%, 28%, and 17%, where the percentages reflect the % of TOA spending in the 1st to the fourth year respectively.

Table 2 lists the weighted aircraft procurement (WAP) costs based on the four year spending profile. This is a rolling calculation, i.e.,

$$\mathrm{WAP_t} = 1 \Big/ \left(\frac{15\%}{RAP_t} + \frac{40\%}{RAP_{t+1}} + \frac{28\%}{RAP_{t+2}} + \frac{17\%}{RAP_{t+3}} \right) , \tag{3}$$

where the WAP in year t is a function of the RAP in year t and the next three future years, i.e., $t+1 \ldots t+3$.

3.4 Foreign Exchange Rate

The foreign exchange rate is a major area for cost risk and uncertainty. The NATO AGS contract will be a firm-fixed price direct commercial sale to Northrop Grumman, with a ceiling price denominated in 2007 base-year euros, but with much of the work done in the United States. Converting from dollars to euros, then, is a major issue.

The prevailing view in the international finance community is that exchange rates are not predictable, especially at short horizons. There is really no reliable method to forecast exchange rates. Models for exchange rate movements are largely driven by changes in macroeconomic factors like unexpected economic or political events, interest rates, the pattern of trade between one country and another and what is known as absolute purchasing power parity (PPP) which holds that goods-market arbitrage will tend to move the exchange rate to equalize prices between countries.

For forecasting, the random walk model remains appealing because it leads to smaller forecasting errors than most other exchange rate models. In simple terms, the exchange rate is, at any moment of time, as likely to rise as it is to fall. For a simple random walk, the best forecast of tomorrow's rate is today's rate, i.e.,

$$X_t = \mu + X_{t-1} + \sigma \varepsilon_t , \tag{4}$$

where X_t is the exchange rate at time t, μ is the expected rate of growth, σ is the standard deviation, and ε_t is a random disturbance term. Figure 4 shows 100 possible sample paths for the U.S. dollar/euro exchange rate from January 2011, with the 95th percentile bounded by dashed lines. Although the exchange rate is varying wildly about an expected value of 1.3306 from January 2011, the U.S. currency has lost 13 percent of its value against the euro since the beginning of the year. Conversely, the euro has risen in value, and has even approached the symbolic \$1.50 threshold. For this analysis, we have fixed the U.S./euro exchange rate at \$1.40/euro with the variability forming a large part of the risk analysis for this study.

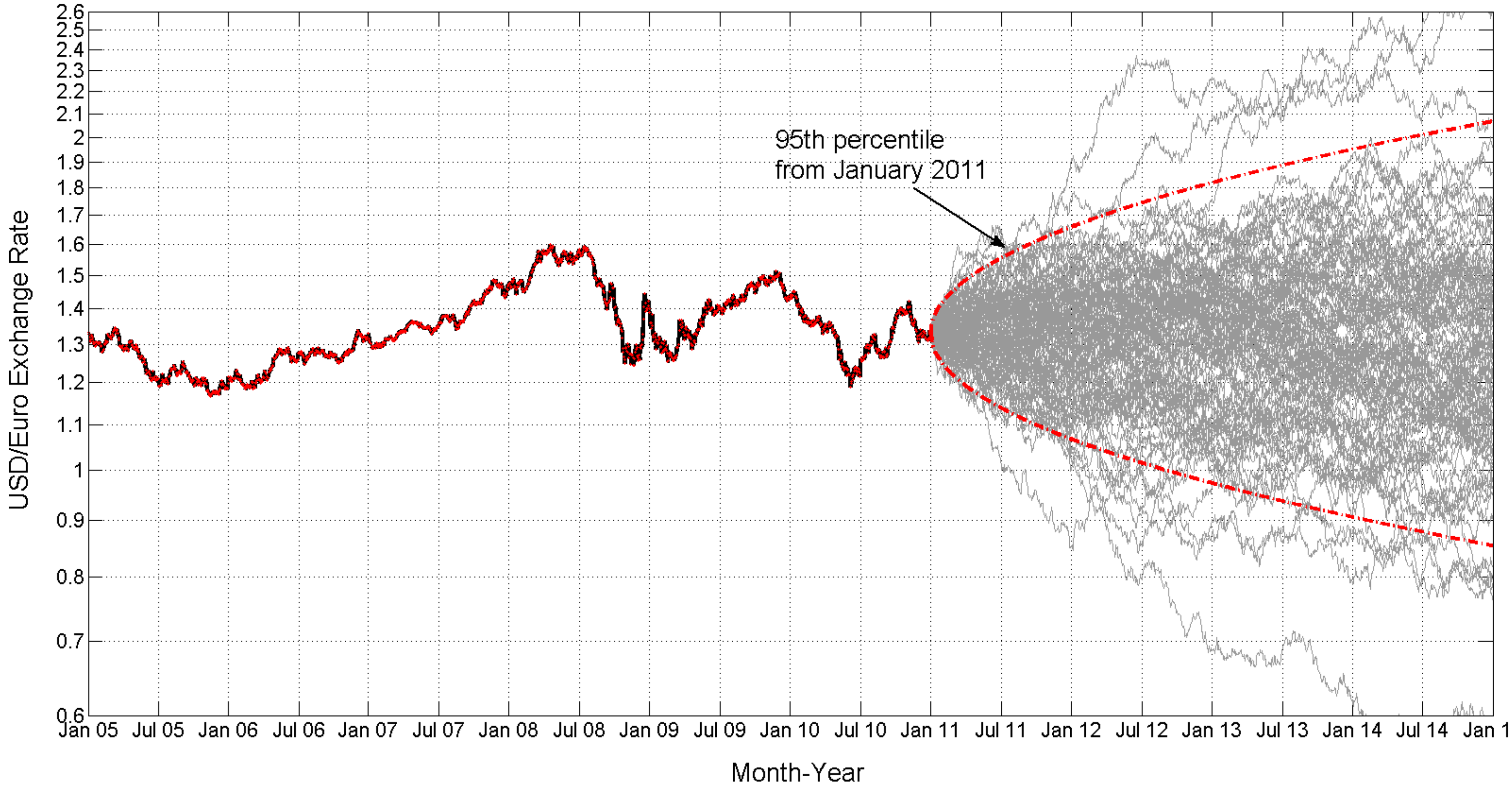


Figure 4: U.S. dollar/euro historical and forecasted exchange rate

4.0 THE AGS COST ESTIMATE

The next, and probably the most critical, step in formulating the ICE consists of developing the cost estimate, which is often seen as an iterative process as costs are refined through time and previously unknown sources become available. The latter becomes particularly acute in developing the ICE for a system that is still only in the development phase.

The steps involved include:

1. Select methods and models
2. Collect, normalize and analyze data
3. Develop Cost Estimating Relationships (CERs)
4. Develop cost model
5. Analyze uncertainties

Each segment of the cost breakdown structure (Table 1) will be analyzed in turn.

4.1 The Air Vehicle

Cost Element 1.1 in Table 1 is the air vehicle. To cost the air vehicle, we start by breaking down each unit into its various components: wing, fuselage, empennage and subsystems, i.e., nacelle, fairings, landing gear, etc (see Figure 5 for an early production RQ-4 schematic). The cost of each component is based on the production schedule for the block 40 UAV with baseline cost adjustments to account for inflation within a staggered production line.

Table 3 shows the Global Hawk low rate initial production (LRIP)[6] with phased deliveries as vehicles advance in technologies[7]. For example, Block 10 aircraft (Basic RQ-4A) consists of seven air vehicles with basic imagery sensors, whereas the Block 40 advanced RQ-4B (Phase 4) will feature MP-RTIP sensor technology, increased payload, wingspan and length, although the range has been reduced due to the increased size and payload [8].

We model air vehicle costs based on Global Hawk Block 30 and 40 actual costs using learning curves[8] , i.e.,

$$\hat{Y} = ax^b \,, \tag{5}$$

where $\hat{Y}$ is the cost associated with lot midpoint quantity x, the coefficient a is the cost associated with the first production unit, and b, the natural learning curve slope in log-space, is always negative implying that unit costs decrease as production increases.

The lot midpoint is a single point that represents the entire lot, and not simply the middle point of the lot. An estimate for the lot midpoint is defined by the equation [9]:

$$\left(U_F + U_L + 2\left(U_F \times U_L\right)^{\frac{1}{2}}\right) \Big/ 4 \,, \tag{6}$$

[6] Low rate initial production (LRIP) is used in U.S. military procurement programs to indicate the phase of initial, small-quantity production of a weapon system.

[7] The acquisition of NATO AGS has continually slipped. Further delays will increase then-year dollar and euro costs due to inflation.

[8] A learning curve, also known as cost improvement curve (and probably better suited to our analysis since there is really no learning involved), states that the cost of delivering items that are produced later in the project should be less than the cost of producing similar items early in the project.

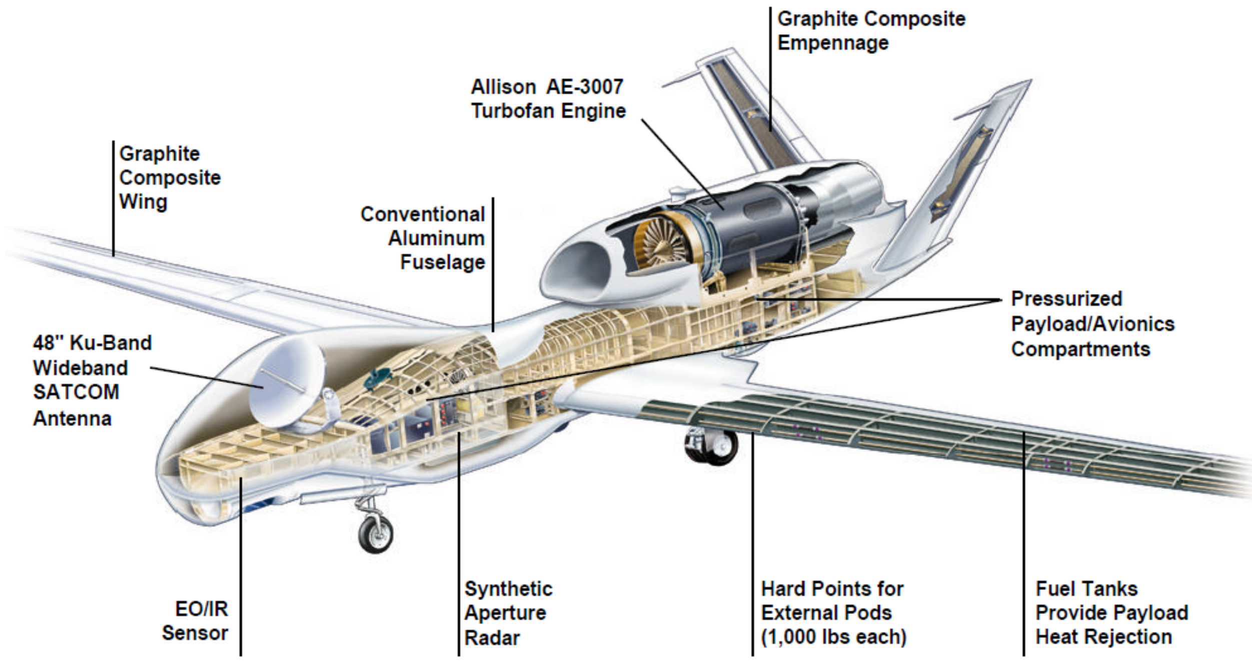


Figure 5: Northrop Grumman Global Hawk air vehicle features. Northrop Grumman approved for public release August 12, 1999 (Distribution Unlimited)

where U_F and U_L denote the first and last units produced respectively in that year. Values for the midpoint can be found in the last line of Table 3.

4.1.1 The Airframe Wing

In September 2002, Triumph Aerostructures - Vought Aircraft Division was selected by Northrop Grumman to build an enhanced wing for the RQ-4 Global Hawk. The division is responsible for wing fabrication, assembly and structural testing. Delivery of the first enhanced wing occurred in July 2005 for LRIP Lot 4. Unit costs for Lots 4, 5 and 6 Block 30 and 40 were used together with the lot midpoints to establish the form of the learning curve based on eqn. (5). Table 4 lists the unit costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2.

Regressing the natural logs of the FY 2010 unit costs against ln(Lot Midpoint) yields a straight line with R^2 of 0.974, Mean Squared Error of 5.069×10^{-4}, and test statistics found in Table 5. Converting back from log-space yields the learning curve[9]

$\hat{Y} =$ [redacted] $\times$ (Lot Midpoint)[redacted] . (7)

Equation 7 is plotted in Figure 6[10] with the actual Lots 4, 5 and 6 costs highlighted as “Actual Unit Costs”. Knowing the lot midpoints for AGS production (Table 3), we can extract the estimated AGS unit wing costs, highlighted in red as “Estimated Unit Costs”.

[9] Values have been sanitized due to business sensitivity.
[10] The Y-scale has been removed due to business sensitivity.

Table 3: U.S. Global Hawk RQ-4 production line

	FY02[a]	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14
U.S. Global Hawk LRIP	Lot 1	Lot 2	Lot 3	Lot 4	Lot 5	Lot 6	Lot 7	Lot 8	Lot 9	Lot 10	Lot 11	Lot 12	Lot 13
Block 10 Aircraft	3	3	1										
Block 20 Aircraft			3	3									
Block 30 Aircraft				1	4	5	2	2	2	2	3	3	3
Block 40 Aircraft					1		3	3	2	2	2	2	2
Department of the Navy BAMS													
SDD Units[b]									2				
LRIP APN[c]												3	
FRP[d] APN													4
NATO AGS													
DDQ[e]										**2**			
Production											**2**	**2**	**2**
Block 30 and 40 Yearly Totals				1	5	5	5	5	6	6	7	10	11
Block 30 and 40 Cumulative				1	6	11	16	21	27	33	40	50	61
First unit in lot				1	2	7	12	17	22	28	34	41	51
Last unit in lot				1	6	11	16	21	27	33	40	50	61
Approximate lot midpoint				1	3.7	8.9	13.9	18.9	24.4	30.4	36.9	45.4	55.9

[a] 01 October 2001 to 31 September 2002

[b] System development and demonstration (SDD) contract awarded to Northrop Grumman in April 2008 [10].

[c] Air Procurement Navy (APN), represents the type of money or appropriation the U.S. is using to buy the UAVs.

[d] Full rate production (FRP)

[e] Design, Development & Qualification

Table 4: U.S. Global Hawk RQ-4 wing costs

FY	Lot	Unit Costs (TY \$000)	Unit Costs (FY10 \$000)	Lot Midpoint
2005	4	[redacted]	[redacted]	1
2006	5	[redacted]	[redacted]	3.7
2007	6	[redacted]	[redacted]	8.9

Table 5: U.S. Global Hawk RQ-4 wing regression statistics

	Coefficient	Standard Error	p-value	t-value
Constant	[redacted]	1.23×10^{-2}	0.0009	722.15
ln(Lot Midpoint)	[redacted]	8.31×10^{-3}	0.0600	-10.57

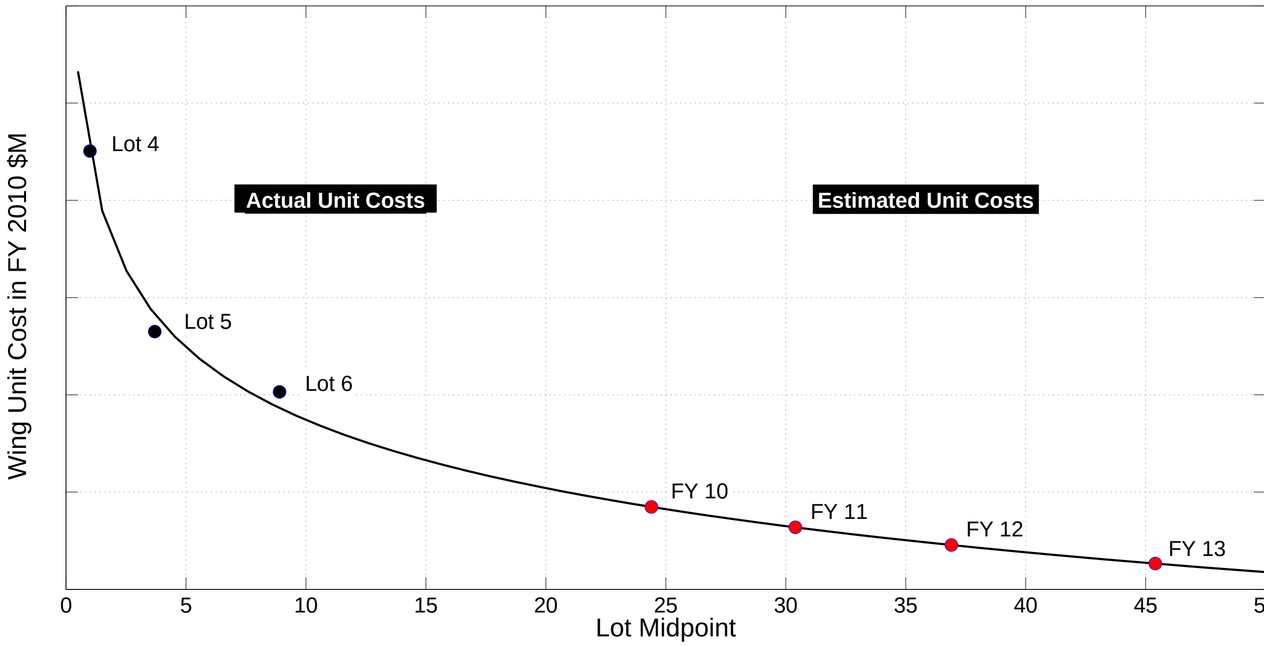


Figure 6: Estimated air vehicle wing unit costs in U.S. FY 10 $M

4.1.2 The Airframe Fuselage

Global Hawk's fuselage consists of three pieces: forward-section, mid-section and aft-section. All three sections are fabricated and mated at Northrop Grumman's Moss Point, Miss. Unmanned Systems Center.

As for the airframe wing, unit costs for Lots 4, 5 and 6 Block 30 and 40 were used together with the lot midpoints to establish the form of the learning curve based on eqn. (5). Table 6 lists the unit costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2.

Table 6: U.S. Global Hawk RQ-4 fuselage costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)	Lot Midpoint
2005	4	[redacted]	[redacted]	1
2006	5	[redacted]	[redacted]	3.7
2007	6	[redacted]	[redacted]	8.9

Regressing the natural logs of the FY 2010 unit costs against ln(Lot Midpoint) yields a straight line with R^2 of 0.841, Mean Squared Error of 4.22×10^{-3}, and test statistics found in Table 7. Converting back from log-space yields the learning curve

$$\hat{Y} = \text{[redacted]} \times (\text{Lot Midpoint})^{\text{[redacted]}}. \quad (8)$$

Equation 8 is plotted in Figure 7 with the actual Lots 4, 5 and 6 costs highlighted as "Actual Unit Costs".

Table 7: U.S. Global Hawk RQ-4 fuselage regression statistics

	Coefficient	Standard Error	p-value	t-value
Constant	[redacted]	3.54×10^{-2}	0.0031	202.59
ln(Lot Midpoint)	[redacted]	2.40×10^{-2}	0.1564	-3.99

Knowing the lot midpoints for AGS production (Table 3), we can extract the estimated AGS unit fuselage costs, highlighted in red as "Estimated Unit Costs".

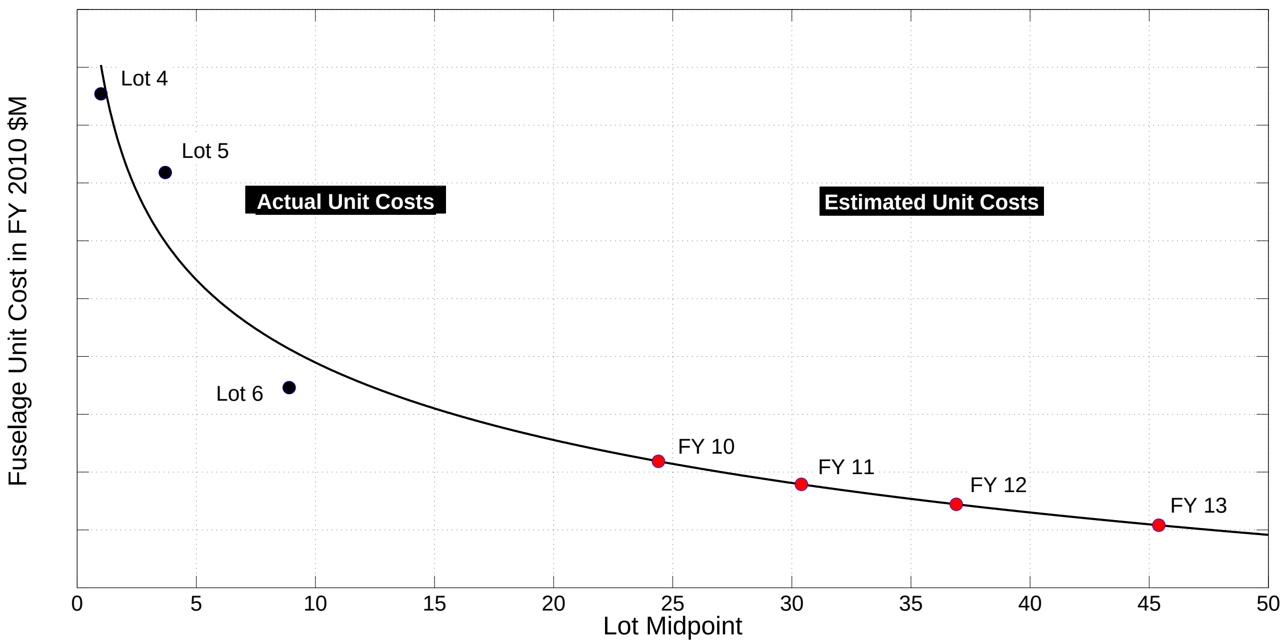


Figure 7: Estimated air vehicle fuselage unit costs in U.S. FY 10 $M

4.1.3 The Airframe Empennage

Since 1995, Aurora Flight Sciences composite manufacturing plant in Bridgeport, W.Va. has been responsible for the fabrication and assembly of the two-spar cantilevered V-tail empennage structure and nacelles systems, and since 2003 has also built most of the composite parts on the Global Hawk fuselage [11].

The unit costs for Lots 4, 5 and 6 Block 30 and 40 were used together with the lot midpoints to establish the form of the learning curve based on eqn. (5). Table 8 lists the unit costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2.

Regressing the natural logs of the FY 2010 unit costs against ln(Lot Midpoint) yields a straight line with R^2 of 0.995, Mean Squared Error of 1.31×10^{-4}, and test statistics found in Table 9. Converting back from log-space yields the learning curve

$\hat{Y} =$ [redacted] $\times$ (Lot Midpoint)[redacted] . (9)

Table 8: U.S. Global Hawk RQ-4 empennage costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)	Lot Midpoint
2005	4	[redacted]	[redacted]	1
2006	5	[redacted]	[redacted]	3.7
2007	6	[redacted]	[redacted]	8.9

Table 9: U.S. Global Hawk RQ-4 empennage regression statistics

	Coefficient	Standard Error	p-value	t-value
Constant	[redacted]	6.23×10^{-3}	0.0006	1111.75
ln(Lot Midpoint)	[redacted]	4.22×10^{-3}	0.0255	-24.94

Equation 9 is plotted in Figure 8 with the actual Lots 4, 5 and 6 costs highlighted as "Actual Unit Costs". Knowing the lot midpoints for AGS production (Table 3), we can extract the estimated AGS unit empennage costs, highlighted in red as "Estimated Unit Costs".

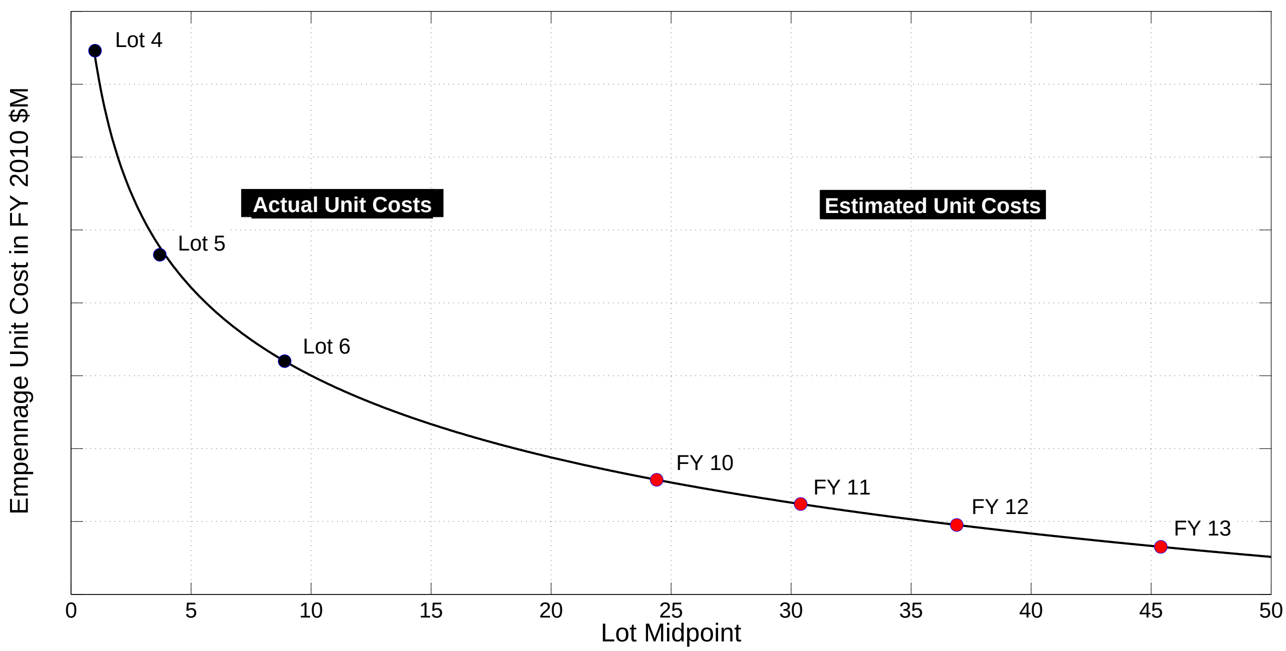


Figure 8: Estimated air vehicle empennage unit costs in U.S. FY 10 $M

4.1.4 The Airframe Subsystems

Global Hawk subsystems include nacelles, fairings, landing gear and other miscellaneous components. Table 10 lists the unit costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2. Results for a learning curve analysis were not statistically significant, consequently the subsystems costs were estimated using the mean value of the costs in lots 4 through 6.

Table 10: U.S. Global Hawk RQ-4 subsystems costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)
2005	4	[redacted]	[redacted]
2006	5	[redacted]	[redacted]
2007	6	[redacted]	[redacted]
		Mean Unit Cost =	[redacted]

4.2 Global Hawk Propulsion

Cost Element 1.1.2 in Table 1 is the powerplant. With 8,600 lbs of thrust, Global Hawk uses the Rolls Royce AE 3007 turbofan engine. The AE3007H is a military variant of the commercial engine that is installed on air vehicles such as the Embraer RJ 145, ERJ 135, ERJ 140, and Cessna Citation X [12].

Table 11 lists the unit costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2. Results for a learning curve analysis were not statistically significant, consequently the engine cost was estimated using the mean value of the costs in lots 4 through 6.

Table 11: U.S. Global Hawk RQ-4 powerplant costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)
2005	4	[redacted]	[redacted]
2006	5	[redacted]	[redacted]
2007	6	[redacted]	[redacted]
		Mean Unit Cost =	[redacted]

4.3 Communications

Cost Element 1.1.3 in Table 1 are communications, which includes an L3 Communications Integrated Communications System (ICS) as a multi-link wideband communication system. The ICS provides a Common Data Link compatible, full duplex wideband air-to-ground and satellite data link, and redundant full duplex UHF satellite and/or Line-of-Sight (LOS) links for command/control. The ICS consists of a Common Airborne Modem Assembly, a SATCOM Radio Frequency Assembly (RFA), a SATCOM antenna, a LOS RFA, a LOS dual-band antenna, two UHF Receiver/Transmitters, two UHF Power Amplifiers, and two UHF antennas [13].

4.3.1 Datalinks

Table 12 lists the unit costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2. Results for a learning curve analysis were not statistically significant, consequently the datalink costs were estimated using the mean value of the costs in lots 4 through 6.

Table 12: U.S. Global Hawk RQ-4 datalinks costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)
2005	4	[redacted]	[redacted]
2006	5	[redacted]	[redacted]
2007	6	[redacted]	[redacted]
		Mean Unit Cost =	[redacted]

4.3.2 Ku Band Satellite Radio

The Global Hawk Mission Control Centre has data up- and down-links to the Global Hawk vehicle directly and via the Ku satellite and the UHF satellite systems.

The unit costs for Lots 5 and 6 Block 30 and 40 were used together with the lot midpoints to establish the form of the learning curve based on eqn. (5). Table 13 lists the unit costs for lots 5 and 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2.

Table 13: U.S. Global Hawk RQ-4 Ku band satellite radio costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)	Lot Midpoint
2006	5	[redacted]	[redacted]	3.7
2007	6	[redacted]	[redacted]	8.9

Regressing the natural logs of the FY 2010 unit costs against ln(Lot Midpoint) yields a straight line with coefficients 6.970 for the Constant and -0.053 for the ln(Lot Midpoint). Converting back from log-space yields the learning curve

$$\hat{Y} = \text{[redacted]} \times (\text{Lot Midpoint})^{\text{[redacted]}}. \tag{10}$$

Equation 10 is plotted in Figure 9 with the actual Lots 5 and 6 costs highlighted as “Actual Unit Costs”. Knowing the lot midpoints for AGS production (Table 3), we can extract the estimated AGS unit Ku band satellite radio costs, highlighted in red as “Estimated Unit Costs”.

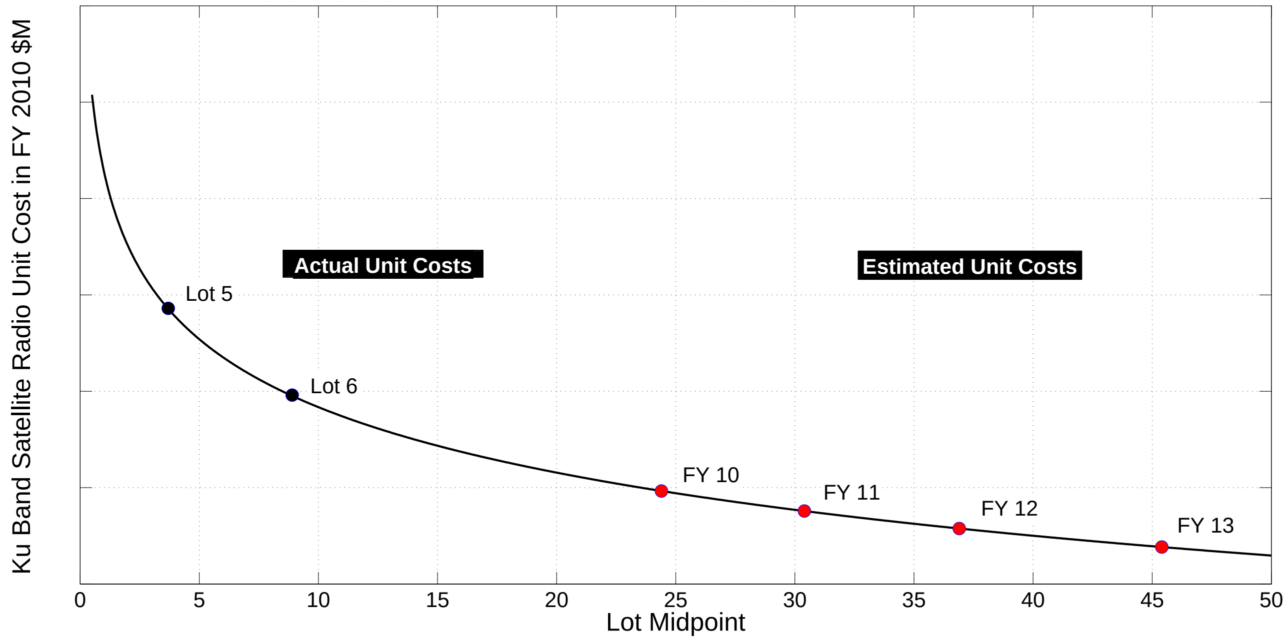


Figure 9: Estimated Ku band satellite radio unit costs in U.S. FY 10 $M

4.3.3 Satellite Communications (SATCOM) Voice

The unit costs for Lots 4, 5 and 6 Block 30 and 40 were used together with the lot midpoints to establish the form of the learning curve based on eqn. (5). Table 14 lists the unit costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2.

Table 14: U.S. Global Hawk RQ-4 SATCOM voice costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)	Lot Midpoint
2005	4	[redacted]	[redacted]	1
2006	5	[redacted]	[redacted]	3.7
2007	6	[redacted]	[redacted]	8.9

Regressing the natural logs of the FY 2010 unit costs against ln(Lot Midpoint) yields a straight line with R^2 of 0.937, Mean Squared Error of 4.12×10^{-3}, and test statistics found in Table 15. Converting back from log-space yields the learning curve

$$\hat{Y} = \text{[redacted]} \times (\text{Lot Midpoint})^{\text{[redacted]}}. \tag{11}$$

Equation 11 is plotted in Figure 10 with the actual Lots 4, 5 and 6 costs highlighted as “Actual Unit Costs”. Knowing the lot midpoints for AGS production (Table 3), we can extract the estimated AGS unit SATCOM voice costs, highlighted in red as “Estimated Unit Costs”.

Table 15: U.S. Global Hawk RQ-4 SATCOM voice regression statistics

	Coefficient	Standard Error	p-value	t-value
Constant	[redacted]	3.50×10^{-2}	0.0040	157.39
ln(Lot Midpoint)	[redacted]	2.37×10^{-2}	0.0943	-6.70

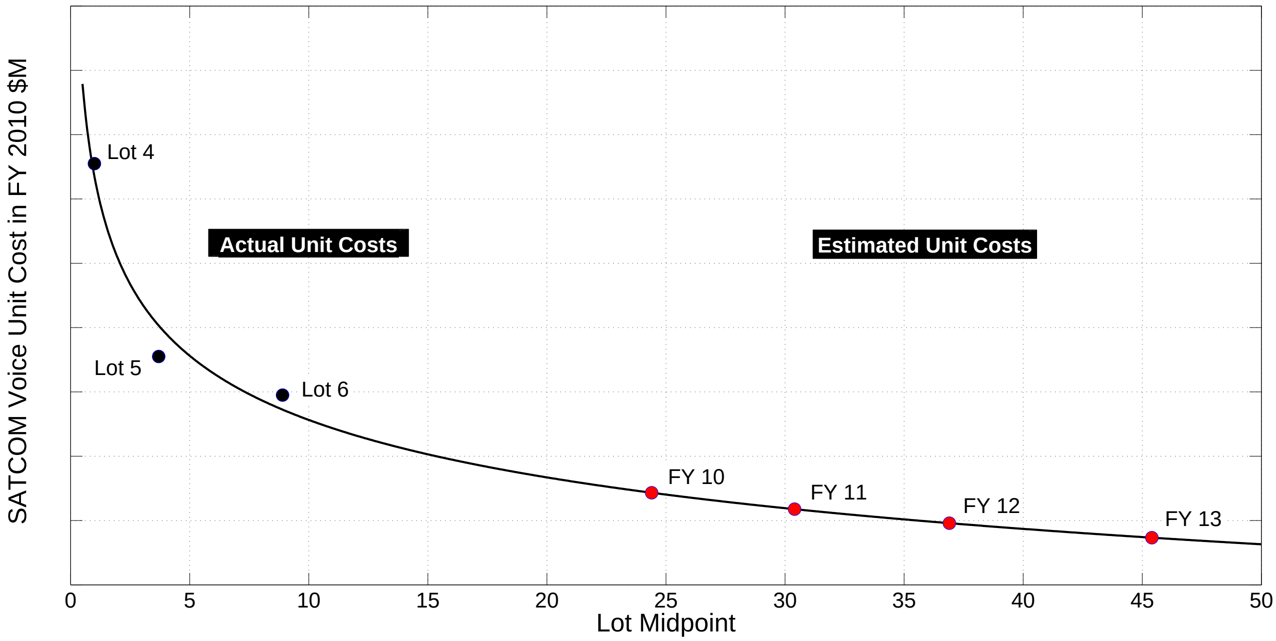


Figure 10: Estimated air vehicle SATCOM voice unit costs in U.S. FY 10 $M

4.3.4 International Maritime SATCOM

The unit costs for Lots 5 and 6 Block 30 and 40 were used together with the lot midpoints to establish the form of the learning curve based on eqn. (5). Table 16 lists the unit costs for lots 5 and 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2.

Table 16: U.S. Global Hawk RQ-4 Maritime SATCOM costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)	Lot Midpoint
2006	5	[redacted]	[redacted]	3.7
2007	6	[redacted]	[redacted]	8.9

Regressing the natural logs of the FY 2010 unit costs against ln(Lot Midpoint) yields a straight line with coefficients 5.348 for the Constant and -0.191 for the ln(Lot Midpoint). Converting back from log-space yields the learning curve

$$\hat{Y} = \text{[redacted]} \times (\text{Lot Midpoint})^{\text{[redacted]}}. \tag{12}$$

Equation 12 is plotted in Figure 11 with the actual Lots 5 and 6 costs highlighted as "Actual Unit Costs". Knowing the lot midpoints for AGS production (Table 3), we can extract the estimated AGS unit Maritime band satellite radio costs, highlighted in red as "Estimated Unit Costs".

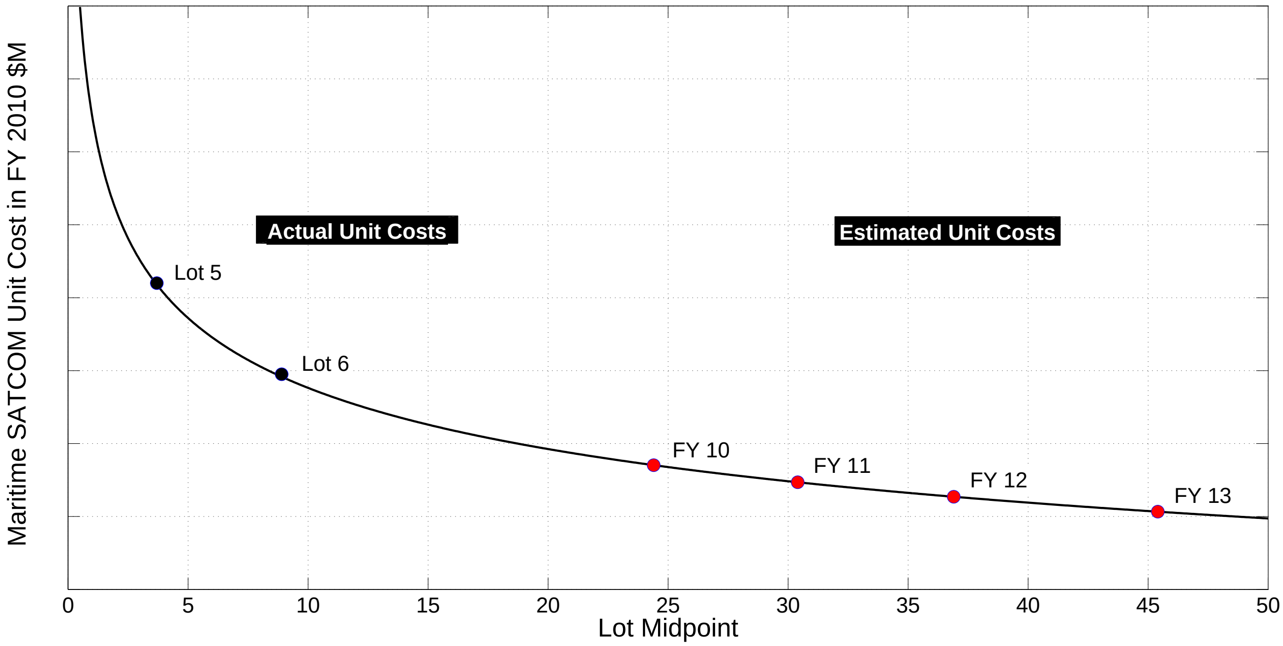


Figure 11: Estimated Maritime SATCOM unit costs in U.S. FY 10 $M

4.3.5 UHF/VHF Communications

The unit costs for Lots 4, 5 and 6 Block 30 and 40 were used together with the lot midpoints to establish the form of the learning curve based on eqn. (5). Table 17 lists the unit costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2.

Table 17: U.S. Global Hawk RQ-4 UHF/VHF communications costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)	Lot Midpoint
2005	4	[redacted]	[redacted]	1
2006	5	[redacted]	[redacted]	3.7
2007	6	[redacted]	[redacted]	8.9

Regressing the natural logs of the FY 2010 unit costs against ln(Lot Midpoint) yields a straight line with R^2 of 0.963, Mean Squared Error of 1.808×10^{-4}, and test statistics found in Table 18. Converting back from log-space yields the learning curve

$$\hat{Y} = \text{[redacted]} \times (\text{Lot Midpoint})^{\text{[redacted]}}. \tag{13}$$

Table 18: U.S. Global Hawk RQ-4 UHF/VHF communications regression statistics

	Coefficient	Standard Error	p-value	t-value
Constant	[redacted]	7.32×10^{-3}	0.0009	695.41
ln(Lot Midpoint)	[redacted]	4.96×10^{-3}	0.0713	-8.89

Equation 13 is plotted in Figure 12 with the actual Lots 4, 5 and 6 costs highlighted as "Actual Unit Costs". Knowing the lot midpoints for AGS production (Table 3), we can extract the estimated AGS unit UHF voice costs, highlighted in red as "Estimated Unit Costs".

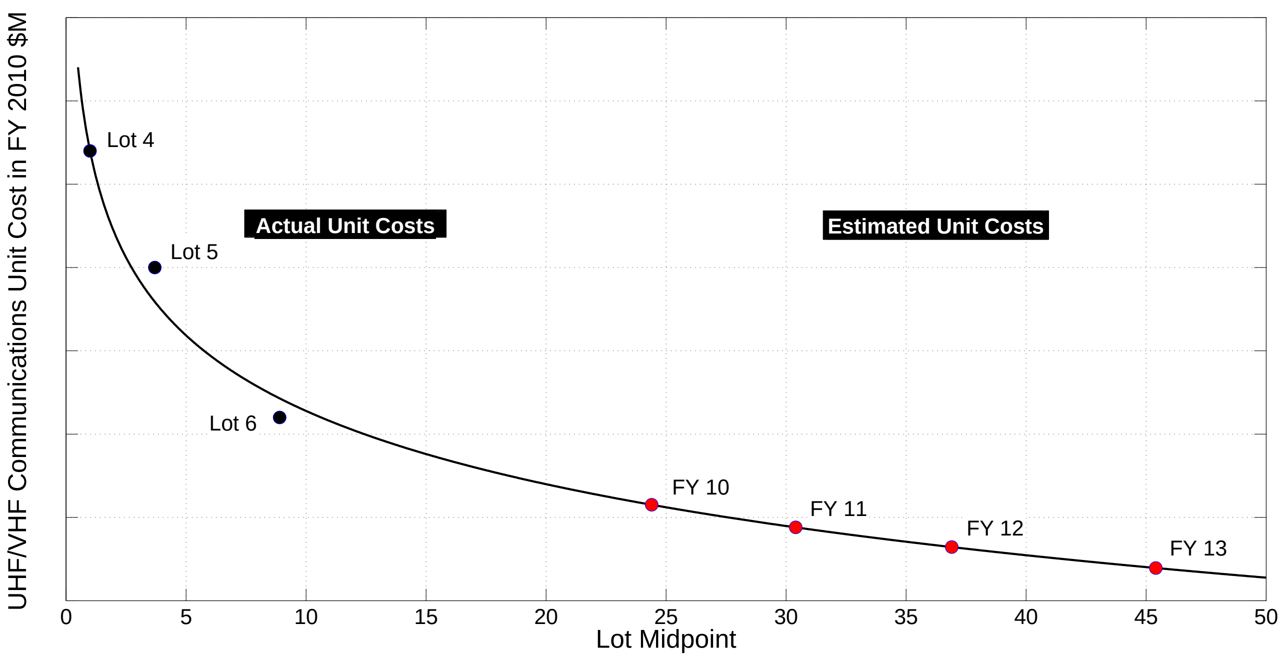


Figure 12: Estimated air vehicle UHF/VHF communication unit costs in U.S. FY 10 $M

4.4 Navigation/Guidance

Cost Element 1.1.4 in Table 1 is Navigation/Guidance, which is via inertial navigation with integrated Global Positioning System updates. Costs were estimated using learning curves and cost means where statistical significance was lacking.

4.4.1 Global Positioning Systems (GPS)

The costs for two GPS units from Lots 4, 5 and 6 Block 30 and 40 were used together with the lot midpoints to establish the form of the learning curve based on eqn. (5). Table 19 lists the two-unit costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2.

Table 19: U.S. Global Hawk RQ-4 GPS two-unit costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)	Lot Midpoint
2005	4	[redacted]	[redacted]	1
2006	5	[redacted]	[redacted]	3.7
2007	6	[redacted]	[redacted]	8.9

Regressing the natural logs of the FY 2010 two-unit costs against ln(Lot Midpoint) yields a straight line with R^2 of 0.999, Mean Squared Error of 1.226×10^{-6}, and test statistics found in Table 20. Converting back from log-space yields the learning curve

$$\hat{Y} = \text{[redacted]} \times (\text{Lot Midpoint})^{\text{[redacted]}} . \quad (14)$$

Table 20: U.S. Global Hawk RQ-4 GPS two-unit regression statistics

	Coefficient	Standard Error	p-value	t-value
Constant	[redacted]	6.03×10^{-4}	0.0001	10183.08
ln(Lot Midpoint)	[redacted]	4.09×10^{-4}	0.0082	-77.67

Equation 14 is plotted in Figure 13 with the actual Lots 4, 5 and 6 costs highlighted as “Actual two-Unit Costs”. Knowing the lot midpoints for AGS production (Table 3), we can extract the estimated AGS two-unit GPS costs, highlighted in red as “Estimated two-Unit Costs”.

4.4.2 OmniStar Differential Global Positioning System (DGPS)

Table 21 lists the unit costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2. Results for a learning curve analysis were not statistically significant, consequently the DGPS costs were estimated using the mean value of the costs in lots 4 through 6.

4.4.3 IFF Transponder/Traffic Alert & Collision (TCAS-II)

Table 22 lists the unit costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2. Results for a learning curve analysis were not statistically significant, consequently the DGPS costs were estimated using the mean value of the costs in lots 4 through 6.

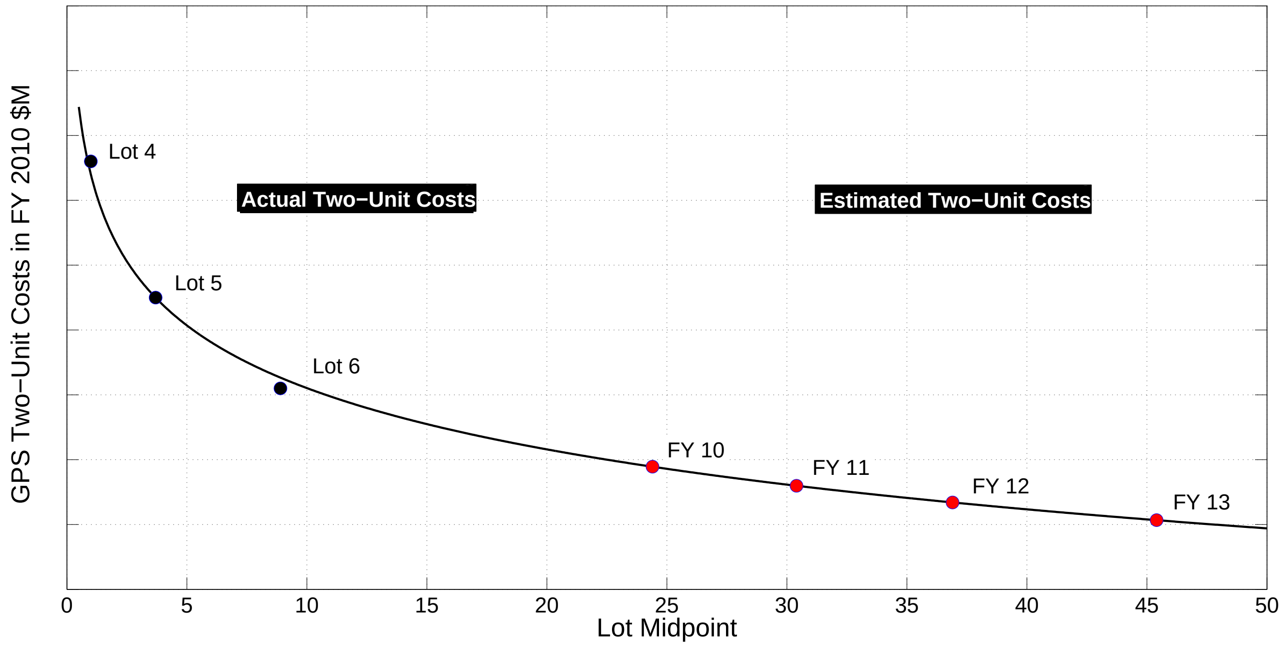


Figure 13: Estimated air vehicle GPS two-unit costs in U.S. FY 10 $M

Table 21: U.S. Global Hawk RQ-4 DGPS costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)
2005	4	[redacted]	[redacted]
2006	5	[redacted]	[redacted]
2007	6	[redacted]	[redacted]
		Mean Unit Cost =	[redacted]

Table 22: U.S. Global Hawk RQ-4 TCAS-II costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)
2005	4	[redacted]	[redacted]
2006	5	[redacted]	[redacted]
2007	6	[redacted]	[redacted]
		Mean Unit Cost =	[redacted]

4.4.4 Worldwide Operations Hardware Suite

Table 23 lists the unit costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2. Results for a learning curve analysis were not statistically significant, consequently the suite costs were estimated using the mean value of the costs in lots 4 through 6.

Table 23: U.S. Global Hawk RQ-4 operations hardware suite costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)
2005	4	[redacted]	[redacted]
2006	5	[redacted]	[redacted]
2007	6	[redacted]	[redacted]
		Mean Unit Cost =	[redacted]

4.5 Miscellaneous Air Vehicle Components

Cost Elements 1.1.5, 1.1.6 and 1.1.7 in Table 1 refer to the central computer, auxiliary equipment and integration, assembly, test and checkout respectively.

4.5.1 The Central Computer

The costs for the central computer from Lots 4, 5 and 6 Block 30 and 40 were used together with the lot midpoints to establish the form of the learning curve based on eqn. (5). Table 24 lists the central computer costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2.

Table 24: U.S. Global Hawk RQ-4 central computer costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)	Lot Midpoint
2005	4	[redacted]	[redacted]	1
2006	5	[redacted]	[redacted]	3.7
2007	6	[redacted]	[redacted]	8.9

Regressing the natural logs of the FY 2010 central computer costs against ln(Lot Midpoint) yields a straight line with R^2 of 0.927, Mean Squared Error of 1.079×10^{-3}, and test statistics found in Table 25. Converting back from log-space yields the learning curve

$$\hat{Y} = \text{[redacted]} \times (\text{Lot Midpoint})^{\text{[redacted]}} . \quad (15)$$

Equation 15 is plotted in Figure 14 with the actual Lots 4, 5 and 6 costs highlighted as “Actual Costs”. Knowing the lot midpoints for AGS production (Table 3), we can extract the estimated AGS unit Computer costs, highlighted in red as “Estimated two-Unit Costs”.

Table 25: U.S. Global Hawk RQ-4 central computer regression statistics

	Coefficient	Standard Error	p-value	t-value
Constant	[redacted]	1.79×10^{-2}	0.0015	417.37
ln(Lot Midpoint)	[redacted]	1.21×10^{-2}	0.1019	-6.19

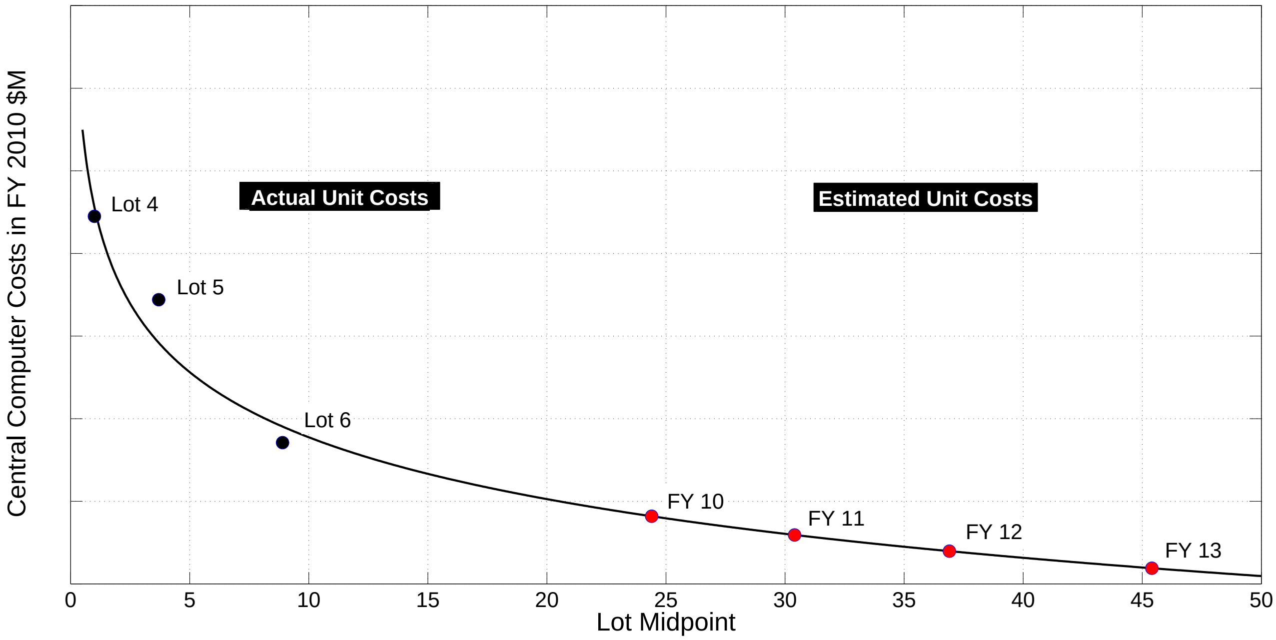


Figure 14: Estimated air vehicle computer two-unit costs in U.S. FY 10 $M

4.5.2 Auxiliary Equipment

Table 26 lists the unit costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2. Results for a learning curve analysis were not statistically significant, consequently the auxiliary equipment costs were estimated using the mean value of the costs in lots 4 through 6.

Table 26: U.S. Global Hawk RQ-4 auxiliary equipment costs

FY	Lot	Unit Costs (TY $000)	Unit Costs (FY10 $000)
2005	4	[redacted]	[redacted]
2006	5	[redacted]	[redacted]
2007	6	[redacted]	[redacted]
		Mean Unit Cost =	[redacted]

4.5.3 Integration, Assembly, Test & Checkout (IATC)

Sensor integration, assembly and full flight testing are major steps towards finalizing operational deployment of the NATO AGS system. The costs for the IATC from Lots 4, 5 and 6 Block 30 and 40 were used together with the lot midpoints to establish the form of the learning curve based on eqn. (5). Table 27 lists the IATC costs for lots 4 through 6 in thousands of TY dollars (col. 3), which were converted to 2010 CY dollars using the WAP rates of Table 2.

Table 27: U.S. Global Hawk RQ-4 Integration, Assembly, Test & Checkout costs

FY	Lot	Unit Costs (TY \$000)	Unit Costs (FY10 \$000)	Lot Midpoint
2005	4	[redacted]	[redacted]	1
2006	5	[redacted]	[redacted]	3.7
2007	6	[redacted]	[redacted]	8.9

Regressing the natural logs of the FY 2010 IATC costs against ln(Lot Midpoint) yields a straight line with R^2 of 0.958, Mean Squared Error of 2.446×10^{-3}, and test statistics found in Table 28. Converting back from log-space yields the learning curve

$$\hat{Y} = \text{[redacted]} \times (\text{Lot Midpoint})^{\text{[redacted]}}. \quad (16)$$

Table 28: U.S. Global Hawk RQ-4 Integration, Assembly, Test & Checkout regression statistics

	Coefficient	Standard Error	p-value	t-value
Constant	[redacted]	2.69×10^{-2}	0.0018	346.71
ln(Lot Midpoint)	[redacted]	1.83×10^{-2}	0.0765	-8.28

Equation 16 is plotted in Figure 15 with the actual Lots 4, 5 and 6 costs highlighted as “Actual Costs”. Knowing the lot midpoints for AGS production (Table 3), we can extract the estimated AGS IATC costs, highlighted in red as “Estimated Costs”.

4.6 The Payloads

Cost Element 1.2 in Table 1 are the payloads, which include MP-RTIP radar, Electronic Support Measures (ESM), Radar Warning Receiver (RWR), Identification Friend or Foe (IFF) Interrogator, and Payloads Integration Assembly and Checkout.

4.6.1 Multi-Platform Radar Technology Insertion Program (MP-RTIP)

Since December 2000, Raytheon and Northrop Grumman have coordinated the design, development and production of MP-RTIP. Its X-band Active Electronically Scanned Array (AESA) radar uses beam steering that can couple electronic and mechanical options. Since costing for the MP-RTIP sensor is not available to NATO, the ICE team based its estimate on an analogous AESA system currently fielded on a variety of platforms

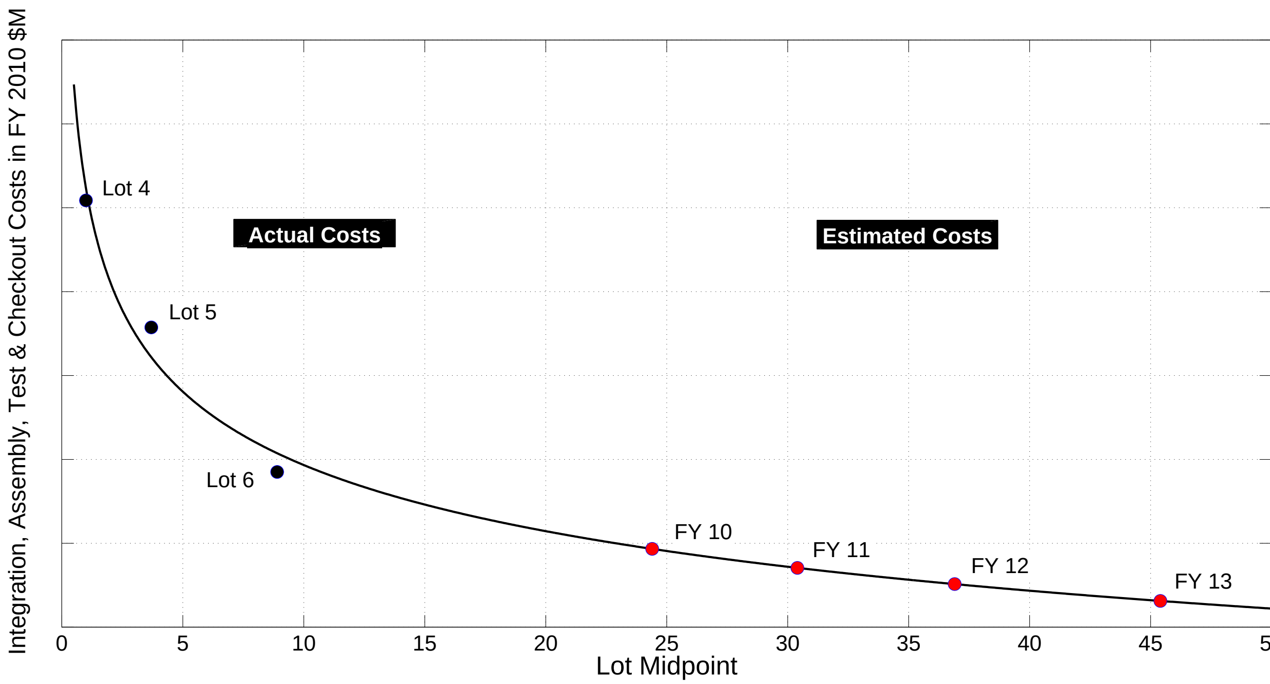


Figure 15: Estimated air vehicle Integration, Assembly, Test & Checkout costs in U.S. FY 10 $M

(including the F/A-18E/F Super Hornet), as a proxy variable for complexity and scale. Using a weight-based analogy, where it was assumed that the higher the weight the greater the cost, the ratio multiplication factor for AGS MP-RTIP (3,000 lbs) to AESA (650 lbs), was given as

$$\text{Ratio} = \frac{\text{MP}-\text{RTIP}}{\text{AESA}} = \frac{3000}{650} = 4.6 \,. \tag{17}$$

From the theory of learning curves [9], each time the quantity of items produced doubles, the cost decreases by a constant percentage known as the *Learning Curve Slope (LCS)*. In log-space, equation (5) becomes a straight line with slope

$$b = \ln(LCS)/\ln(2) \,, \tag{18}$$

where the term $\ln(2)$ arises from the doubling of items.

From the contractor cost data report for LRIP AESA production, the total TY 2003 price for eight units is [redacted]. The U.S. independent cost estimate on AESA determined a learning curve slope of 90%, which gives a value for b of [redacted]. Equation (5) can therefore be re-written as

$$\hat{Y} = \sum_{i=1}^{8} \alpha Q_i^{\text{[redacted]}} \,, \tag{19}$$

where $\hat{Y} =$ [redacted] is the total Lot 1 cost, Q_i is the i^{th} unit of production, and α is the first unit cost, which is

$$\alpha = \frac{\hat{Y}}{\sum_{i=1}^{8} Q_i^{\text{[redacted]}}} = \frac{\text{[redacted]}}{\left[1^{\text{[redacted]}} + 2^{\text{[redacted]}} + \cdots + 8^{\text{[redacted]}}\right]} = \text{TY [redacted]} = \text{[redacted] in FY 2010} \,, \tag{20}$$

where the TY cost was converted to 2010 CY dollars using the WAP rates of Table 2.

The final MP-RTIP estimated unit cost is given by

$$\text{Ratio} \times \alpha \times 0.90 = \text{[redacted]} \text{ in FY 2010}, \tag{21}$$

where the factor of 0.90 accounts for the learning on the AESA radar for the F/A-18 E/F Super Hornet aircraft.

4.7 The Ground/Support Segment

The system architecture and the configuration of the NATO AGS ground segment are especially developed to accommodate a network centric approach, with emphasis on a local area network design and real-time exchange of data between AGS users. Also, the use of standardization will ensure system interoperability, not only with the NATO C3I systems, but also national ISR systems. Through the AGS ground segment, NATO forces will also have access to nationally acquired reconnaissance and surveillance data [14].

The following elements of the AGS Ground System (GS) are based on information from the NATO Alliance Ground Surveillance Management Agency (NAGSMA). They reflect the assumed numbers to be purchased.

- Main Operating Station (MOS) (1 Element)
  - Located at Sigonella Air Base in Italy, the Main Operating Station (MOS), together with training and logistic support elements, provides the virtual aircrew for UAV and ground entity coordination for multiple air vehicles within different theatres of operations. This capability provides UAV command and control as well as information management with interoperable NATO and National C2ISR systems.
  - Costs for the operator and UAV flight trainers are included in the overall costs for the MOS.
- Mobile General Ground Stations (MGGS) (11 Elements)
  - Includes 11 all terrain vehicles with shelters.
- Transportable General Ground Stations (TGGS) (4 Elements)
  - Includes 4 transportable shelters with workstations and communications equipment.
- Mobile General Communications Stations (MGCS) (15 Elements)
  - 11 all terrain communications vehicles with SATCOM and wide band datalink packages are included in the costs for the MGGS.
  - 4 all terrain communications vehicles with SATCOM and wide band datalink packages are included in the costs for the TGGS.
- UAV Command and Control Elements (UCE) (5 Elements)
  - The UCE provides aircraft control, communications, navigation plan modification, and differential global positioning system equipment to support aircraft takeoff and landing, sensor task scheduling and management. Included are the costs for five transportable shelters with workstations and communications equipment.
- Remote Workstations (22 Elements)

– Costs for the 22 remote workstations are included in the overall costs for the MGGS.

The AGS GS is partially comparable to the GS for the U.S. Global Hawk. The U.S. Standard Ground System consists of the Ground Station Launch and Recovery Element (LRE) and the Mission Control Element (MCE), whereas the LRE GS is quite comparable to the UCE from AGS, the elements and functions from the MCE are distributed to the MOS and other mobile GS.

Typically, the hardware components the stations consist of shelters, controls and displays, exterior equipment for electrical power and environmental control and also communication devices for SATCOM (UHF, Ku-Band, Inmarsat for mobile voice and data communications), tactical common data, wideband datalink line-of-sight (WBDL-LOS) capability and air traffic control communications.

The basis for the estimation of the AGS Ground Segments has been generated by available information from U.S. Global Hawk Ground Stations. It is assumed that there is a comparable use of components as utilized in the U.S. GS, e.g., work stations, radios, and antennas for the different communication channels.

4.7.1 AGS Ground Segment Parametric Cost Estimation

The SAS 076 task group decided to carry out the cost estimation for the Ground Stations via a parametric cost estimation model. Parametric estimating is a technique that uses validated relationships between a project's known technical, programmatic, and cost characteristics and known historical resources consumed during the development, manufacture, and/or modification of an end item. A number of parametric techniques exist that practitioners can use to estimate costs. These techniques include cost estimating relationships (CERs) and parametric models. Parametric models are more complex than CERs because they incorporate many equations, ground rules, assumptions, logic, and variables that describe and define the particular situation being studied and estimated.

Parametric cost estimation models are designed so that they can conduct cost estimation with less hardware information. Therefore they are an appropriate tool to estimate the AGS GS. Missing input values can be replaced by internal default values or tabular values. For the AGS GS, the cost estimation model "Advanced Cost Estimating Systems (ACES)" was used[11]. A general description of the model is provided in Appendix A1.

4.7.2 Ground Segment Hardware

A work breakdown structure for the Ground Stations (Table 29) has been derived via a top down approach from documents of the default Global Hawk GS, where it has been assumed that the systems in the AGS GS are the same as in the default Global Hawk GS. This can be derived from the communication channels (Ku SATCOM, INMARSAT, UHF SATCOM, Common data link (CDL) line of sight, UHF/VHF voice) as they are implemented in both systems.

The basic configuration of the stations is described in documents from the U.S. Ground Stations, but without any specifications. Input values for elements of the GS have been compiled by expert interviews, internet research, and from national documents. If no references have been specified, the input values should be treated as best assumptions.

The following information is required for the cost estimation:

- Physical Characteristics (mechanical / electronic item; weight; volume)

[11] The analysis in this section was completed by Germany. Consequently, translation from German to English was required for input and output ACES software screenshots.

Table 29: The cost breakdown structure for NATO AGS ground Segment

WBS #	Cost Element	WBS #	Cost Element
1.3	**AGS Ground Segment (GS) and Support Segment**	1.3.1.2.1.4.1	Antenna Unit
1.3.1	**Hardware**	1.3.1.2.1.4.2	Trailer
1.3.1.1	**Main Operation Support (MOS) [1x]**	1.3.1.2.1.5	MGGS Terrain Communication Equipment
1.3.1.1.1	MOS Operation Equipment	1.3.1.2.1.5.1	MGCE Communication Vehicle
1.3.1.1.1.1	MOS Crew Workstations (30 Workstations)	1.3.1.2.1.5.2	MGCE VHF/UHF Communication and SATCOM
1.3.1.1.1.2	MOS Displays	1.3.1.2.1.5.3	MGCE HF Communication
1.3.1.1.1.3	MOS Processing Unit	1.3.1.2.1.5.4	Other Communication Equipment
1.3.1.1.1.4	MOS Printer	1.3.1.2.1.6	MGGS Miscellaneous / Cabling
1.3.1.1.2	MOS Sensor Communication	1.3.1.2.1.7	I&T MGGS
1.3.1.1.2.1	Antenna Unit	1.3.1.3	**Transportable General Ground Station (TGGS) [4x]**
1.3.1.1.2.2	Ku-Antenna Unit	1.3.1.3.1	TGGS Shelter
1.3.1.1.2.3	Wideband Modem Assembly (WMA)	1.3.1.3.2	TGGS Crew Workstations (3x)
1.3.1.1.2.4	CDL Interfacebox (CIB)	1.3.1.3.2.1	TGGS Processing Unit
1.3.1.1.2.5	DC Control / Amp assy	1.3.1.3.2.2	TGGS Map Computer
1.3.1.1.2.6	AC Power Control	1.3.1.3.2.3	TGGS Antenna Controller
1.3.1.1.2.7	Gigabit Switch	1.3.1.3.2.4	TGGS Monitor (2x)
1.3.1.1.2.8	Internal Cables and Wiring	1.3.1.3.2.5	TGGS Printer
1.3.1.1.2.9	Computer	1.3.1.3.2.6	TGGS Software
1.3.1.1.2.10	Cables	1.3.1.3.3	TGGS Sensor Communication System
1.3.1.1.3	MOS Communication Equipment	1.3.1.3.3.1	TGGS Transit Package No. 1
1.3.1.1.3.1	MOS VHF/UHF Communication and SATCOM	1.3.1.3.3.2	TGGS Transit Case No. 2
1.3.1.1.4	MOS Other Equipment	1.3.1.3.3.3	TGGS Antenna Subsystem
1.3.1.1.5	MOS Training Facility	1.3.1.3.4	TGGS Terrain Communication Equipment
1.3.1.1.5.1	AGS Operator Trainer	1.3.1.3.4.1	TGGS Communication Vehicle
1.3.1.1.5.2	UAV Flight Trainer	1.3.1.3.4.2	TGGS VHF/UHF Communication and SATCOM
1.3.1.1.5.3	MOS Training Processing Unit	1.3.1.3.4.3	TGGS HF Communication
1.3.1.1.6	MOB Software	1.3.1.3.4.4	Other Communication Equipment
1.3.1.1.7	MOB Test & Integration	1.3.1.3.5	TGGS Environmental Control System
1.3.1.2	**Mobile General Ground Station (MGGS) [11x]**	1.3.1.3.6	TGGS Electrical System
1.3.1.2.1	MGGS All Terrain Vehicle /w Shelter	1.3.1.3.7	TGGS Miscellaneous / Cabling
1.3.1.2.1.1	MGGS Terrain Vehicle	1.3.1.3.8	I&T TGSS
1.3.1.2.1.2	MGGS Shelter	1.3.1.4	**UAV Command & Control Element (UCE) [5x]**
1.3.1.2.1.2.1	MGGS Container (protected)	1.3.1.4.1	UCE Shelter
1.3.1.2.1.2.2	MGGS Crew Workstations (5 incl. 2 Remoteable Workstations)	1.3.1.4.1.1	UCE Container (protected)
1.3.1.2.1.2.3	MGGS Sensor Communication (indoor unit)	1.3.1.4.1.2	UCE Crew Workstations (2x)
1.3.1.2.1.2.4	MGGS Environmental Control System	1.3.1.4.1.3	UCE and Communication Equipment
1.3.1.2.1.2.5	MGGS Software	1.3.1.4.1.4	UCE Software
1.3.1.2.1.3	MGGS Electrical System	1.3.1.4.2	UCE Electrical System
1.3.1.2.1.3.1	Power Supply Generator	1.3.1.4.2.1	Power Supply Generator
1.3.1.2.1.3.2	Power Distribution Unit	1.3.1.4.2.2	Power Distribution Unit
1.3.1.2.1.3.3	Trailer	1.3.1.4.3	UCE Int & Test
1.3.1.2.1.4	MGGS Antenna Subsystem (outdoor unit)	1.3.1.5	**GS Test & Integration**

- Quantity (Production Quantity, Lot Quantity)
- Quality (operating environment factor, Technology difficulty Index of the mechanical or electronics portions).
- Economic (currency, escalation, Year of Economics, Country of Production, G&A Profit, Cost of money)
- Development (Engineering Difficulty; quantity of prototypes)
- System relationship (integration complexity)

4.7.3 Sample Calculation: VHF/UHF Antenna

To understand how ACES was used in this context, we present the case for the VHF/UHF ground station antenna. The manufacturer is unknown at this stage, however the Harris RF-9070 is a militarized, vertically polarized, omnidirectional transportable antenna designed for ground-to-air communication for use in other UAVs [15], and as such was used as a proxy for the AGS ground stations.

Figure 16 provides the technical specifications for the RF-9070. From the parameters, input values for the ACES estimation tool were generated. In this case, the weight and type of the antenna is linked with inherent tool values (e.g., production complexity, integration complexity, operational environment) as shown in Figure 17. The tool then generates the probable production costs, and on higher integration levels, the costs for integration and test (see Figure 18 and Appendix A2 for translation from German to English). Generally the estimation is based on the assumption that military off-the-shelf components will be used.

The final estimated cost for the VHF/UHF antenna can be found in Figure 18 in the row labelled, in German, “Gesamtkosten” (Total Sum) (See Appendix A2 for definitions). These costs include, in 2009 USD, $27,415 for development, $115,991 for production, for a total cost of $143,406 for 11 units, or $13,037 per unit.

Specifications for the RF-9070

Electrical

- **Frequency Range**
  100 to 400 MHz (usable 90 to 470 MHz)
- **RF Power Capacity**
  400 watts
- **Input Impedance**
  50 ohm, nominal
- **Radiation Pattern**
  Omnidirectional
- **Polarization**
  Vertical
- **VSWR**
  ≤2.1 typical, 2.5:1 maximum
- **Gain**
  >2 dBi

Environmental

- **Temperature**
  Operating: –40° to +55° C (–40° to +131° F) Storage: –60° to +70° C (–76° to +158° F)
- **Relative Humidity**
  0 to 100%

Mechanical

- **RF Connector**
  Female, Type N
- **Deployed Dimensions**
  76H x 60D in (193H x 152D cm)
- **Finish**
  E512 per MIL-F-14072
- **Weight**
  20 lb (9.1 kg)
- **Mounting Interface**
  1.3 inch (3.3cm) threaded hole in center hub
- **Installation time**
  10 minutes, 2 people

Options

- RF-9071 Mounting Mast — A 6.5-foot (2-m) length of 1.3-inch (3.3-cm) diameter mast complete with mounting clamps. The mast is threaded at one end with an 11-1/2 NPT thread to match the antenna hub.

Figure 16: Harris RF-9070 parameters

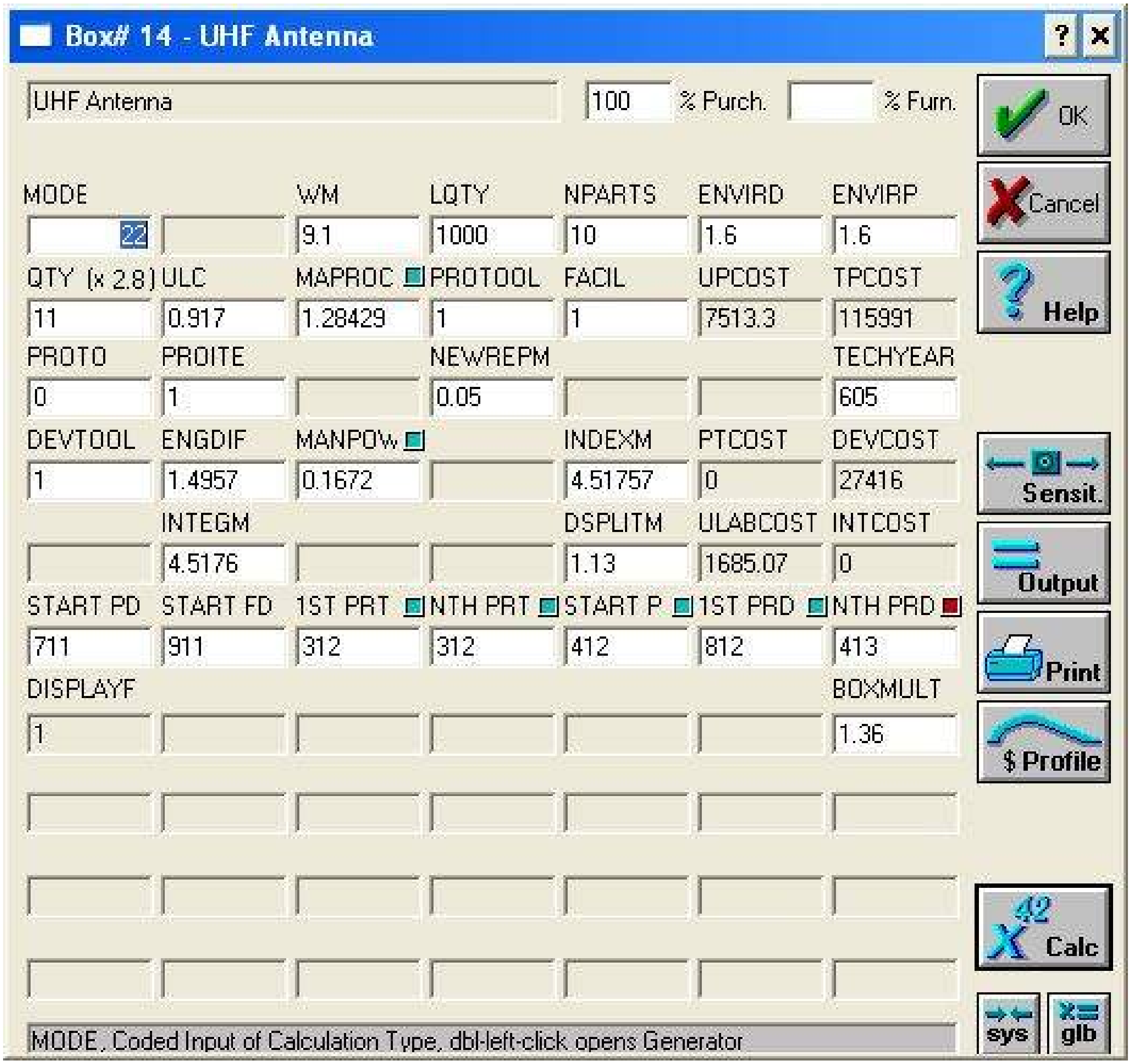
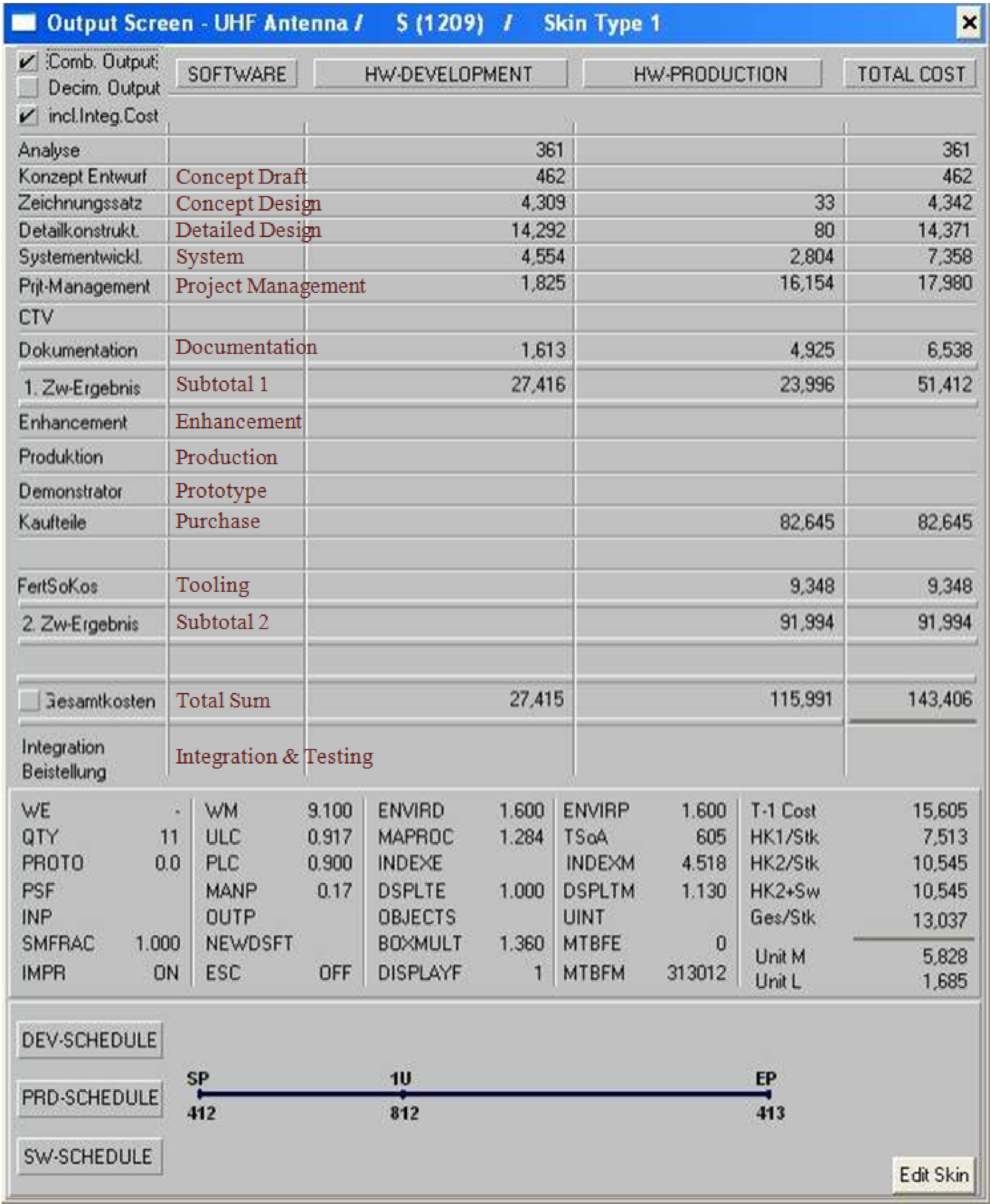


Figure 17: Harris RF-9070 input to ACES



		SOFTWARE	HW-DEVELOPMENT	HW-PRODUCTION	TOTAL COST
Analyse			361		361
Konzept Entwurf	Concept Draft		462		462
Zeichnungssatz	Concept Design		4,309	33	4,342
Detailkonstrukt.	Detailed Design		14,292	80	14,371
Systementwickl.	System		4,554	2,804	7,358
Prjt-Management	Project Management		1,825	16,154	17,980
CTV					
Dokumentation	Documentation		1,613	4,925	6,538
1. Zw-Ergebnis	Subtotal 1		27,416	23,996	51,412
Enhancement	Enhancement				
Produktion	Production				
Demonstrator	Prototype				
Kaufteile	Purchase			82,645	82,645
FertSoKos	Tooling			9,348	9,348
2. Zw-Ergebnis	Subtotal 2			91,994	91,994
Gesamtkosten	Total Sum		27,415	115,991	143,406
Integration Beistellung	Integration & Testing				

Figure 18: Harris RF-9070 output from ACES

5.0 RISK AND UNCERTAINTY ANALYSIS FOR NATO AGS

5.1 Background

The SAS-076 Task Group used Enhanced Scenario-Based Method (eSBM) [16] to perform risk and uncertainty cost analysis for the AGS acquisition. To conduct eSBM, the Task Group needed to

- Generate a point estimate for acquisition costs,
- Identify the position of the point estimate on the S-Curve,
- Identify and analyze major elements of risk and uncertainty,
- Select an appropriate Coefficient of Variation (CV),
- Develop scenarios, and
- Combine these components into an integrated whole.

5.2 Point Estimate and Position on S-Curve

The Task Group employed a number of techniques to estimate the costs of AGS system. These included learning curves, averages of historical data, CERs, and analogies. In many cases, cross checks were developed based on German experience with Eurohawk. Since it's necessary in eSBM to anchor a cost estimate to a point on a cumulative probability distribution, baseline costs were generated, by design, at the *median*, or the 50th percentile. Another choice could have been the *mean*. Generally, there's flexibility in choosing either, or perhaps a point in-between.

In the case of AGS, many items in the Cost Element Structure (Table 1), were estimated using unit learning curves or power-function CERs with a multiplicative random error term (e.g., $Y = \alpha Q^{\beta} e^{\varepsilon}$, where $Y =$ unit cost, $Q =$ lot-midpoint quantity, α and β are parameters, i.e., first unit cost on the learning curve (T1) and elasticity respectively, and $\varepsilon = N(\mu, \sigma^2)$ is the error distribution, where we assume the errors are normally distributed with mean μ and standard deviation σ.

Examples include the wing, fuselage, and empennage of the UAV, and final assembly, integration, test and check out (see section 4.1). In these cases, inserting a value of an explanatory variable into the equation yields an estimated median rather than a mean value [17]. In other cases, such as for software development where representatives from several participating nations each generated a cost estimate independently, a middle value (median) was selected as the baseline. Moreover, the CERs employed in producing the middle value were themselves median-yielding power-function equations. In other cases where costs appeared normally distributed, the choice of median or mean was a moot point since the values were equal. Examples include systems engineering and program management, initial spares, and support equipment.

5.3 Risk Elements

Next, the Task Group identified these major areas of cost risk and uncertainty[12]:

[12] Areas of risk were identified based on general knowledge of defense acquisition programs and the discipline of international economics, site visits to Northrop Grumman's International Program Office in Florida and to NATO's AGS Management Agency in Brussels, and on meetings with other key AGS acquisition officials, including the Chairman of the Board of Directors of the NATO AGS Management Organization.

- **Exchange Rate:** The AGS contract will be a firm-fixed price direct commercial sale to Northrop Grumman, with a ceiling price denominated in 2007 base-year euros, but with much of the work done in the United States. Converting from dollars to euros, then, is a major issue. Unfortunately, currency exchange rates are notoriously difficult if not impossible to predict accurately and consistently. The projections of Figure 4, using random walk theory, don't exactly inspire confidence in anyone's ability to hone in on the future value of the $/€ exchange rate.

  Since its introduction roughly a decade ago, the value of the euro has varied from a low of $0.83/€ in 2000 to a peak of $1.60/€ in 2008, a swing of 93%. More recently, during the height of the Greek credit crisis in early 2010, the euro fell to $1.18/€. It then returned to pre-crisis levels only to fall once again with the Irish debt crisis.

- **Inflation:** Inflation rates for AGS design, development and production will likely differ from values recently experienced in the aerospace industries in the United States, Canada, and Europe. The ICE team used a baseline value of 3% inflation per annum for out-year projections, weighted according to the relative contributions of the 14 NATO countries participating in the program. However, as Figure 19 shows, inflation as measured by the consumer price index, seems to be accelerating in Europe as the economic recovery gains traction. Defense inflation generally runs higher than economy-wide figures by perhaps 100 to 300 basis points per year, but follows the same trend. An increase in rates is a risk in the next few years.

Figure 19: Euro area inflation rate (actual change on consumer price index). Source: TradingEconomics.com

- **Schedule:** The acquisition of NATO AGS has continually slipped. Further delays will increase then-year dollar and euro costs due to inflation.

- **Software:** European participants in the AGS program, and Canada, are responsible for ground segment design, development, and build. Elements of the ground segment include several types of ground vehicles, command and control units, training equipment, and an extensive software development effort. The *baseline* count of equivalent source lines of code (ESLOC) is unusually large from a U.S. perspective[13], and includes no factor for *growth*. However, as Figure 20 shows, code growth on defense software development projects has been the norm.

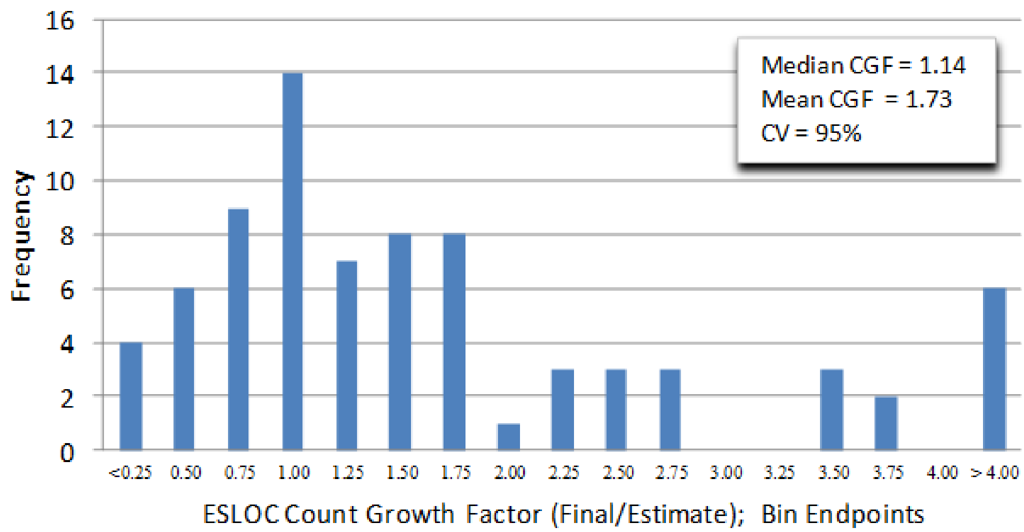


Figure 20: Growth count in estimated lines of code

- **Software (cont'd):** In the case of AGS, software will be developed in many different countries by many different companies, possibly using different computer languages and even operating systems. Levels of Capability Maturity Model Integration (CMMI) certification vary among vendors. Integration of software modules, hardware with software, and AGS with other ISR assets such as ASTOR from the U.K. and Global Hawk from the U.S. will all be required. Configuration management and software integration will be major issues. The AGS ICE team uses the *average* historical growth in ESLOC count as a proxy variable for risk for the entire software development effort.

- **Radar:** The MP-RTIP payload uses advanced electronically scanned array (AESA) technology currently employed on the F/A-18, among other platforms. However, the MP-RTIP development program has experienced significant cost and schedule growth which might translate into higher unit production costs.

- **Int'l. Participation:** 14 NATO countries intend to fund the acquisition of AGS. In return, each demands a fair share of the work. NATO intends to award a contract to Northrop Grumman Integrated Systems Sector International, Inc (NGISSI) who will have total system performance responsibility (TSPR) and will subcontract work to vendors in various countries, with some of the potential firms shown in Figure 21. Developing and producing hardware and software under this work-share constraint in such a multi-cultural, geographically-dispersed environment runs the risk of introducing inefficiencies into the program.

Prime	2nd Level Subs	Country
NGISSII USA	Northrop Grumman Systems Corp (NGSC)	USA
	CASSIDIAN (EADS) Potential subs to Cassidian: Retia ICZ (Czech Republic); Aktors (Estonia); Dati (Latvia); Elsis (Lithuania); Konstrukta (Slovakia); Hermes Soft Lab (Slovenia)	Germany
	Selex Galileo	Italy
	General Dynamics Canada	Canada
	Kongsberg	Norway

3rd Level Subs Nations
Bulgaria
Czech Republic
~~Denmark~~
Estonia
Latvia
Lithuania
Luxemburg
Romania
Slovakia
Slovenia

Figure 21: International participation

- **Affordability:** Fitting the desired numbers and capabilities of UAVs and ground-segment elements under the NATO's ceiling price remains a challenge. A few years ago NATO and industry envisioned a mixed fleet of manned and unmanned air vehicles to perform the ground surveillance mission. However, that option was scrapped because of cost. Affordability continues to be an issue as many European nations struggle to reduce budget deficits and national debt. Denmark, for example, announced its intention in 2010 to withdraw from the program because of budget tightening.

5.4 Selection of CV

With a point estimate generated and major elements of risk identified, the Task Group needed a CV to implement eSBM. NATO, it's important to note, uses the Phased Armaments Programming System (PAPS) as its acquisition framework. In PAPS, AGS is near what we call a Milestone (MS) B decision in the United States. Further, although AGS is an Alliance rather than a U.S. DoD acquisition program, the prime contractor will be Northrop Grumman, and close to two-thirds of the costs will be incurred in the U.S. The use of benchmark CV data from the U.S., then, seems appropriate, especially since none is available for NATO acquisitions.

The Task Group selected a MS B CV of 51% based on the full sample of data for quantity-adjusted then-year dollar acquisition outcomes. That is, the Task Group regarded the quantity of UAVs and ground vehicles as exogenous but the rate of inflation as random, for purposes of generating an S-curve. Given affordability and exchange rate issues, the massive software development effort, and extensive international participation with each country demanding "noble work," the Task Group judged the higher-end of Milestone B CV values to be appropriate.

5.5 Scenarios

The Task Group bundled risks and uncertainties into three scenarios: baseline, pessimistic, and resource-constrained. The baseline scenario used "likely-to-occur" values or assumptions as shown in Figure 22[14]:

- An exchange rate of $1.35 per euro;
- An inflation rate of 3% per annum, based on best-estimates of inflation in the aerospace industries of the U.S., Canada, and Europe, weighted according to program costs to-be-incurred by each;
- Procurement of 8 UAVs and 15 ground-segment vehicles in accordance with NATO's AGS Program Memorandum of Understanding;
- Contract award in late FY2011;
- 91% learning on MP-RTIP, based on analogy to the Advanced Electronically Scanned Array (AESA) radar on the F/A-18 E/F aircraft; and
- Built-in redundancies or contingencies for operating in a NATO acquisition environment.

Elements	Baseline	Pessimistic	Constrained
Exchange rate	$1.35 per €	$x.xx per €	$x.xx per €
Inflation rate	3.00%	x%	x%
Quantities/Schedule	FY11 FY12 FY13 FY14 FY15	slip in schedule: FY11 FY12 FY13 FY14 FY15	FY11 FY12 FY13 FY14 FY15
UAVs	2 2 2 2 0		change in quantities and schedule
Ground Stations			
Transportable	1 1 1 1 0		
Mobile	2 3 3 3 0		
ESLOC Count	No growth	x% increase	No growth
Radar	91% learning	x% learning	91% learning
Int'l Participation	Built-in redundancy	x% delta to SE/PM	Built-in redundancy
Affordability	Unconstrained	Unconstrained	Constrained

Figure 22: Task Group scenarios

In keeping with the tenants of eSBM, the non-baseline scenarios did not represent *extreme* cases, but rather a set of conditions that could easily occur in the future. For example, the *worst imaginable* case for the U.S. dollar or the Euro might be a severe devaluation of either[15]. On the other hand, modest appreciation or depreciation of the dollar or Euro is certainly plausible, depending upon circumstances.

[14] Data that might be construed as business sensitive are omitted from the display.

[15] Pundits in Europe and the U.S. speculated in February 2010, for example, that the European Union, and the Euro, might not survive. Other pundits project financial Armageddon for the U.S. because of our enormous direct national debt ($14 trillion) and unfunded liabilities for Social Security, Medicare, and other entitlement programs (another $50 trillion).

5.6 S-Curve

With a point estimate, CV, and anchored position on the S-curve in hand, Figure 23 shows eSBM results. Values on the X-axis could be construed as somewhat business-sensitive, prior to contract award, and are therefore not displayed.

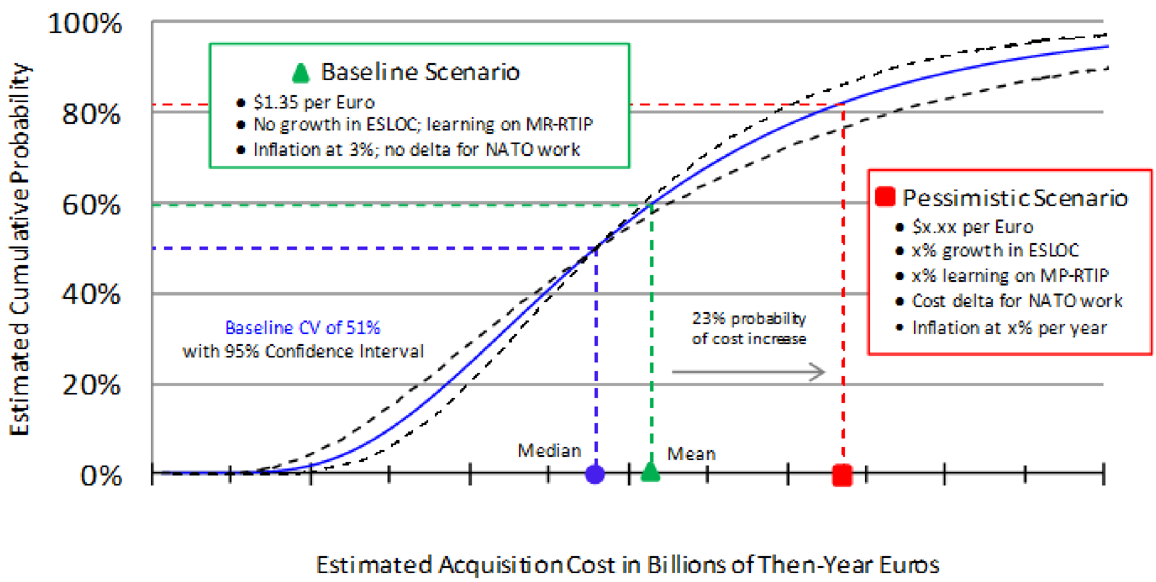


Figure 23: Estimated acquisition cost of NATO AGS (*Cost values are not displayed due to business sensitivity*)

Several points merit emphasis:

- Not all areas of risk and uncertainty are captured in the scenarios, nor do they need to be. That's the great advantage of employing a historically-based CV in computing an S-curve. The distribution implicitly captures the totality of events which will influence the cost of the acquisition. A maintained hypothesis, of course, is that historical variances will continue to hold.
- The scenarios reflect cost estimates for the events or assumptions they portray. In supporting the NATO AGS Management Agency (NAGSMA) in Brussels, the Task Group estimated and presented costs of each element of risk (e.g., the cost impact of a 50% increase in ESLOC count) within a scenario. The associated probabilities for the scenarios were simply read from the S-curve.
- The resource-constrained scenario was not displayed on the S-curve of Figure 6, and was instead regarded as a distinct, separate what-if drill. Estimating the risk and uncertainty of changes in acquisition quantity is generally beyond the purview of cost analysts. The changes often result from Congressional action, which can be hard to predict. The historical CVs presented here are all adjusted for quantity variation; if they weren't, they'd be far higher.
- The probability of NATO AGS acquisition costs increasing from the baseline to the pessimistic scenario is roughly one in four or five. Identification and quantification of this possibility can form the basis of risk-management planning by both the program office (NAGSMA) and the prime contractor.

5.7 S-Curve Excursion

To demonstrate the consequences of using an inaccurate CV, Figure 24 shows a second S-curve based on a hypothetical value of 10%.

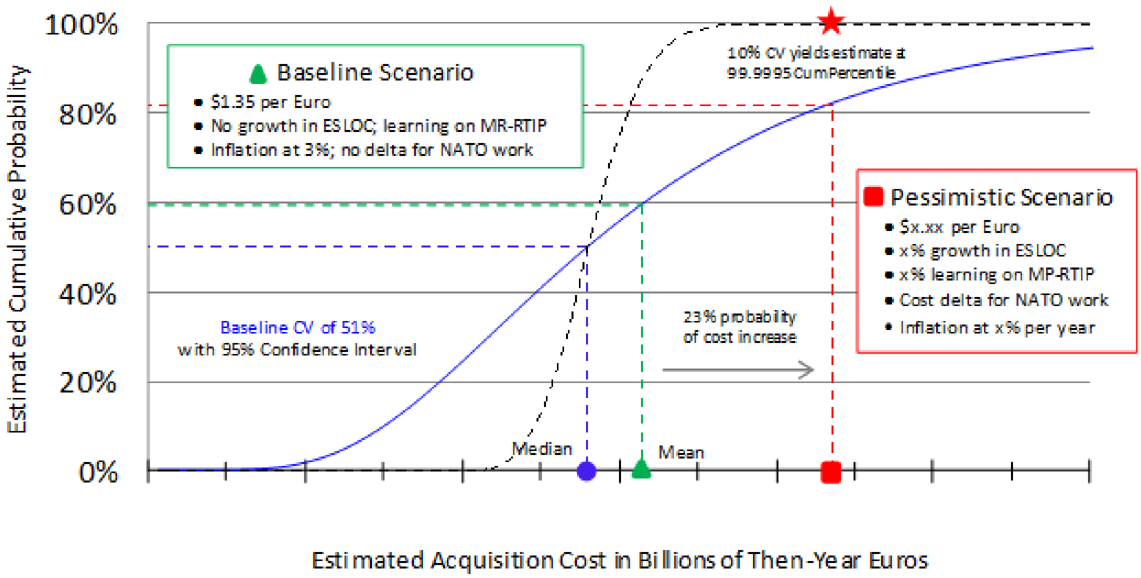


Figure 24: Estimated acquisition cost of NATO AGS (*Cost values are not displayed due to business sensitivity*)

If the 10% value had been used, the probability of costs reaching or exceeding the value of the pessimistic scenario would be calculated as only *five in one million*! Yet, to repeat, the parameters used in this scenario are realistic, modest deltas to the baseline. They include what the Task Group regarded as a very slight change in the exchange rate, a modest increase in the rate of inflation, use of a *mean* growth factor for number of equivalent source lines of code, and a percentage increase in the cost of system engineering/program management due to international participation that at least one member of the team thought was appropriate only if two rather than 14 nations were involved in AGS design, development, and build. In short, the steep S-curve would deceive stakeholders into believing that risk was slight and the probability of significant cost growth minimal.

Specification and adoption of a pessimistic scenario in eSBM, which can easily be adopted in Monte Carlo methodology, too, has the virtue of providing the means with which to perform a sanity check on the value of the CV. If the resulting S-curve is too steep to be plausible, then underlying risk and uncertainty distributions for major cost elements must not have been calculated correctly. Chances are that at least one was too narrow.

Finally, since the mean of a lognormal distribution involves a variance term, use of the steeper S-curve would have resulted in a lower value of expected cost.

6.0 CONCLUSIONS

Working as a coherent team, the Task Group was successful in generating a credible, complete, scientifically-sound independent cost estimate on the NATO AGS acquisition program. Specific cost estimates for the program are business-sensitive information and cannot be published. Nevertheless, these conclusions are offered:

- It is, in fact, possible to generate an ICE on a major acquisition program using an international team of dedicated cost analysts.
- It is difficult but not impossible to share cost data across nations. Non-disclosure forms need to be completed, and information closely held. Further, it is useful if not essential to obtain buy-in early on from major stakeholders. The SAS-076 team generated an ICE development plan and obtained signatures from the Chairman of the Board of AGS Management Organization (NAGSMO), the Director the AGS Management Agency (NAGSMA), and the Director the SAS-076 study group.
- Major elements of cost risk on the program are:
  - Software development;
  - International participation;
  - Exchange rate;
  - Inflation rate; and,
  - MP-RTIP radar.
- The SAS-054 guidelines on methods and models for cost analysis are, in fact, applicable in a cost-estimating environment. The SAS-076 Task Group followed these guidelines extensively and recommends no major changes.

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[17] Goldberger, A. S., "*The Interpretation and Estimation of Cobb-Douglas Functions,"* Econometrica*, Vol. 35, July-October 1968, pp. 464–472.*

Appendix A-1: A GENERAL OVERVIEW OF THE ADVANCED COST ESTIMATING SYSTEMS (ACES)

The parametric hardware, software and built-in life cycle model ACES is a computerized method for deriving cost estimates of electronic and mechanical hardware assemblies and systems, as well as software programs and the complete life cycle analysis. The ACES model combines both hardware and software estimating in one model. The model is applicable to all aspects of hardware and software acquisition from preliminary design to development and production and life cycle costing analysis.

The model estimates the costs associated with design engineering, drafting, project management, documentation, system engineering, special tooling and test equipment, and material, labour and overheads. It also addresses the feasibility of a project by costing a preliminary design phase. Costs to integrate subsystems and assemblies into a system, and to test the system for required operation are also estimated by the model.

The model will compute and display the cost for development and/or production, as well as the software cost categories, separately for the mechanical and electronic parts of the hardware, and can be used to cost electronic or mechanical items individually.

The fundamental parametric data used by ACES are:

- Quantities of equipment to be developed, produced, or otherwise acquired.
- Schedules for preliminary development, full scale development, production, and integration and testing, including lead times for set-up, parts procurement (non-long lead items), and redesign.
- Manpower requirements for engineering and software.
- Hardware geometry consisting of size and weights of electronic and mechanical elements.
- Amount of new design required and complexity of the development engineering task.
- Operational environment and development and production specification requirements.
- Technology difficulty Index of the mechanical and electronics portions of the hardware.
- Fabrication process to be used for production.
- Pertinent escalation rates and mark-ups for general and administrative charges, profit, R&D, cost of money, and material handling.
- Technological state-of-the-art.
- Calculating technology based INDEX factors from any known cost.
- Estimating the individual costs of multiple lot productions.
- Calculating the costs for design integration of purchased equipment.
- Calculating the costs for design integration of furnished equipment
- Calculating technology based indices of non-homogeneous hardware items.
- Modelling any resource expenditure distribution desired.

- Calculating field reliability (MTBF) of electronic and mechanical assemblies.

All of the ACES parameters are dynamically linked to one or more other inputs in computing model results. Usually, a change to one input will require a change to others as well. An example is production quantity. This variable has a direct effect on schedule and manufacturing process. These types of inter-dependencies are what distinguish a model from a calculator.

Appendix A-2: ACES INPUT AND OUTPUT PARAMETER DEFINITIONS

Tables 30–32 define the input and output parameters as they apply to they apply to the Harris RF-9070 UHF/VHF antenna.

Table 30: Input definitions for ACES parameters as they apply to the Harris RF-9070 UHF/VHF antenna

Parameter	Value	Description	Specification
Mode	22	The MODE defines the input required to describe the hardware development and/or production scenario.	MODE 22 is used for an item that is mechanical or structural.
WM	9.1	WM is the weight of mechanical item in kilograms.	Value from the specification.
LQTY	1000	Lot quantity indicates the total size of a production lot when only a portion of the larger production lot is used by the element.	Assumption that the Antenna is part of a larger lot.
ENVIRD	1.6	In general this variable relates the cost of hardware development to the requirements of the environment in which the hardware must operate. It is a measure of the portability, reliability, structure, testing and documentation required for acceptable contract performance.	The recommended value for mobile military equipment.
ENVIRP	1.6	In general this variable relates the cost of hardware production to the requirements of the environment in which the hardware must operate. It is a measure of the portability, reliability, structure, testing and documentation required for acceptable contract performance.	The recommended value for mobile military equipment.
QTY	11	Production Quantity to indicate the number of production units. for the element.	Equal to the number of ground stations.
UCL	0.917	Unit Learning Curve	A typical value for military equipment.
PROTO	0	Number of prototypes	Assumes the antenna is a purchased item and no prototype was necessary.
PROITE	1	Prototype iterations indicate the number of design/redesign cycles needed to complete the final prototype	Using a standard factor for generating design integration cost.
NEWREPM	0.05	New/Repeat mechanical design	Using a low factor for generating design integration cost.
ENGDIF	1.4957	Engineering difficulty	Using recommended mean values
INDEXM	4.51	INDEXM is a measure of the equipment item's technology, its produceability (material, machining and assembly tolerances, machining difficulty and surface finish, etc.).	Using recommended values from an index table inside the tool or calibrated values from other sources.
INTEGM	4.51	Integration difficulty for mechanic. INTEGM defines the level of the structural contribution to the Integration and test effort for this element.	A Table and Generator from the tool is provided to suggest appropriate values.
START PD - NTH PRT		Start and end date for the development.	Dates from the program office.
START P - NTH P		Start and end date for the production.	Dates from the program office.

Table 31: Output definitions for ACES parameters as they apply to the Harris RF-9070 UHF/VHF antenna

Cost Element	Development	Production	Total Cost
Concept Draft, Concept Design, Full Draft, Detail Design	These cost elements contain all costs for drafting the Detailed Design in the development phase.	These cost elements contain all costs for drafting the Detailed Design in the production phase.	
System	This element encompasses the system engineering effort to define the system, and integrated planning and control of the technical program efforts of design engineering, logistic engineering, production engineering and integrated test planning.	Same as the development but limited to production needs.	
Project Management	Project Management includes administrative and technical management and other program-oriented personnel. These costs include all efforts to assure the proper and cost-effective performance of the contract between the customer, the company and its subcontractors.	This cost element is similar to the development effort but limited to monitoring and controlling production activities.	
Documentation	This cost element contains all costs associated with deliverable documentation.	This cost element is similar to the development effort but limited to production items.	
Prototype	These costs include all labour and material required to fabricate, assemble and test the prototypes.		
Tooling	This cost element contains all costs associated with the design, fabrication, purchase and calibration of all special tools, fixtures and test equipment required to handle, build and test prototype components.	Same as the development category but includes production related tooling.	

Table 32: Output definitions (Cont'd) for ACES parameters as they apply to the Harris RF-9070 UHF/VHF antenna

Cost Element	Development	Production	Total Cost
Production		This cost element includes all labour costs involved in the recurring manufacturing efforts to fabricate, assemble. It also includes all material that is contained in the completed article.	
Integration & Testing	This cost element includes all costs associated with the test and integration for this element into the system.	This cost element includes all costs associated with the test and integration for this element in the system.	
T-1 Cost	Cost for the first unit.		Cost for the first unit.
HK1/STk (Unit Production Cost (UPC))	Unit production cost (The unit production cost for the specified production quantity. It includes production labour, material and overhead.)		Unit production cost (The unit production cost for the specified production quantity. It includes production labour, material and overhead.)
HK2/STk (Amortized UPC/Quantity)	Amortized Unit Cost (The Amortized Unit Cost is calculated as Production Total Cost divided by Quantity)		Amortized Unit Cost (The Amortized Unit Cost is calculated as Production Total Cost divided by Quantity)
HK2+Sw (Amortized UPC + Software)	Amortized Unit Cost plus Software costs		Amortized Unit Cost plus Software costs
Ges/Stk (Total Sum/Quantity)			Total costs divided by the quantity

Annex B1

Estimating the Acquisition Cost of the Royal Netherlands Navy Landing Platform Dock Ships: an Ex Post Analysis

NATO RTO Systems Analysis and Studies Task Group-076*

November 1, 2011

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1.0 INTRODUCTION

1.1 Background

This paper documents the SAS-076 Task Group efforts in generating independent estimates of the development and construction costs of the Royal Netherlands Navy landing platform dock ships in a blind, ex post exercise—only after the independent cost estimates were completed did the Task Group obtain information on the actual cost of landing platform dock ships. The differences between the actual and estimated costs were then analyzed.

The Rotterdam class is a Landing Platform Dock (LPD) or amphibious warfare ship of the Royal Netherlands Navy. The lead ship, Her Netherlands Majesty's Ship (HMS) Rotterdam, pennant number L800, was launched in 1997. The second ship of the class, HMS Johan de Witt (L801), was launched in 2007. The ships have a large helicopter deck and a well dock for large landing craft. The class was a joint design between the Netherlands and Spain[1]. HMS Rotterdam is pictured in Figure 1. Although considered the sister ship to

Figure 1: HMS Rotterdam L800 Landing Platform Dock Ship

HMS Rotterdam, HMS Johan de Witt has significant technical differences including longer length, larger displacement, podded propulsion (as oppose to shaft propulsion), increased lift capacity (e.g., fuel, vehicles, etc.), higher superstructure (by one deck), and larger crew capacity. For this reason HMS Johan de Witt's rank in class is set to one.

Following a key recommendation of SAS-054, this report documents two independent methods that were used in generating a cost estimate for HMS Rotterdam and Johan de Witt. The first method, classified as a parametric approach, employs Quinlan's M5 model tree algorithm [1], a system that combines features of decision trees with linear regression models. The second method is an analogy approach based on hierarchical cluster analysis. It considers multiple analogous systems and is void of subjectivity that is typically inherent

[1] The two ships of the Spanish belonging to the Galicia class are the Galicia (commissioned in 1998) and the Castilla (2001).

in analogy approaches. Both data mining approaches are data intensive—the SAS-076 Task Group compiled a database of 57 ships in 16 classes from 6 nations. 136 descriptive, technical, and cost attributes were gathered for each of the ships.

1.2 Objective

The objective of this report is to present two independent methods for generating estimates for the development and production cost of HMS Rotterdam and Johan de Witt LPDs. In an ex post exercise, the actual costs are revealed and compared to the estimates. The report presents a novel application of known data mining algorithms to the problem of ship cost estimation.

1.3 Scope

This report focuses on two data mining approaches: M5 model trees for parametric cost estimation, and hierarchical cluster analysis for costing by analogy. Limitations and assumptions specific to the parametric method are presented in Sections 3.0 and 4.0.

1.4 Outline

Section 2.0 details the multinational data that was gathered (Annex **??** contains data tables continuing from Section 2.0). The parametric cost estimation method is developed in Section 3.0 and applied to the data set. The analogy cost estimation method is developed in Section 4.0 and applied to the data set. The results for the predicted cost of HMS Rotterdam and Johan de Witt LPDs are presented in Sections 5.0 and in particular are compared to the actual costs. Section 6.0 compiles lessons identified, conclusions are presented in Section 7.0, and Annex **??** provides the algorithmic details of the approach.

2.0 DATA

The SAS-076 Task Group compiled a database of 57 ships in 16 classes from 6 nations. The sources of data were culled from SAS-076 participants and publicly-available sources such as Jane's Fighting Warships[2], Federation of American Scientists[3], Navy Matters[4], Forecast International[5], U.S. Naval Institute sources (e.g., [2]), and Wikipedia: The Free Encyclopedia[6]. The ships included cover a span of years (commissioned) from 1954 to 2010. Table 1 lists the ships in the data set. The first three columns indicate the name, pennant number, and type of ship. The subsequent three columns indicate the rank (in class), year of commission, and nationality.

The ships included cover a span of years (commissioned) from 1954 to 2010. Table 1 lists the ships in the data set. The first three columns indicate the name, pennant number, and type of ship. The subsequent three columns indicate the rank (in class), year of commission, and nationality. The data set includes seven ship categories:

- Amphibious Assault Ship (AAS);
- Auxiliary Oiler Replenishment (AOR);

[2]Jane's Fighting Warships: http://jfs.janes.com
[3]Federation of American Scientists: http://www.fas.org/
[4]Navy Matters: http://www.navy-matters.beedall.com
[5]Forecast International: http://www.forecastinternational.com
[6]Wikipedia: The Free Encyclopedia: http://www.wikipedia.com

- Landing Platform Dock (LPD);
- Landing Platform Helicopter (LPH);
- Landing Ship Dock (LSD); and,
- Icebreaker.

Forty of the ships are from the U.S., seven from the United Kingdom, four from France, three from Sweden, two from Canada, and one from Norway.

The SAS-076 ship data set contains military and civilian auxiliary (coast guard or similar) vessels that were judged by the SAS-076 Task Group to be analogous to HMS Rotterdam LPD. The selection of ships for inclusion was primarily driven by the accessibility of costing information, which was limited to the information gathered from national sources by the SAS-076 Task Group representatives[7]. Representatives of the SAS-076 Task Group were solicited to provide technical and cost information for their nation's ships most closely resembling the role or size of a LPD. The decision as to which ships are similar or analogous is subjective.

The novel parametric approach to cost estimation using data mining (to be elaborated in Section 3.0) allows for, or can excel on, a greater variability in the input data set—variability that could be questioned when using traditional parametric approaches. The fidelity of parametric approaches also depends on the size of the input data set. In this case, the availability of ship cost data limited the size of the SAS-076 ship data set. For these reasons, the SAS-076 Task Group decided to include ships such as Sweden's Carlskrona LPD and Atle and Oden icebreakers—leading to the potentially useful data combination of ships of the "right purpose, wrong size" and "wrong purpose, right size" [3].

The SAS-076 Task Group also decided to omit the U.S. San Antonio class LPDs due to its well-documented high cost of ship construction: as of July 2007, the U.S. Navy had invested over 1.75 billion U.S dollars constructing the San Antonio LPD 17, over 800 million dollars over budget [4] (including a mid-construction transfer from Avondale shipyard in New Orleans to the Northrop Grumman shipyard in Mississippi due to poor performance by the former). According to the U.S. Government Accountability Office [5]: "the U.S. Navy's reliance on an immature design tool led to problems that affected all aspects of the lead ship's design. Without a stable design, work was often delayed from early in the building cycle to later, during integration of the hull". The LPD-17 cost was a clear outlier in comparison to the costs of the other ships. It was deemed that its cost was not accurately reflective of its technical attributes.

The selection of technical specifications included was also driven by the availability of public information.

[7] For example, detailed technical information was available for the Italian San Giorgio class and the Spanish Galicia class LPDs, but cost information was unobtainable

Table 1: Description of analogous ships

Name	Number	Type	Rank	Commissioned	Country
Thomaston	LSD 28	LSD	1	1954	United States
Plymouth Rock	LSD 29	LSD	2	1954	United States
Fort Snelling	LSD 30	LSD	3	1955	United States
Point Defiance	LSD 31	LSD	4	1955	United States
Spiegel Grove	LSD 32	LSD	5	1956	United States
Alamo	LSD 33	LSD	6	1956	United States
Hermitage	LSD 34	LSD	7	1956	United States
Monticello	LSD 35	LSD	8	1957	United States
Anchorage	LSD 36	LSD	1	1969	United States
Portland	LSD 37	LSD	2	1970	United States
Pensacola	LSD 38	LSD	3	1971	United States
Mount Vernon	LSD 39	LSD	4	1972	United States
Fort Fisher	LSD 40	LSD	5	1972	United States
Whidbey Island	LSD 41	LSD	1	1985	United States
Germantown	LSD 42	LSD	2	1986	United States
Fort McHenry	LSD 43	LSD	3	1987	United States
Gunston Hall	LSD 44	LSD	4	1989	United States
Comstock	LSD 45	LSD	5	1990	United States
Tortuga	LSD 46	LSD	6	1990	United States
Rushmore	LSD 47	LSD	7	1991	United States
Ashland	LSD 48	LSD	8	1992	United States
Harpers Ferry	LSD 49	LSD	1	1995	United States
Carter Hall	LSD 50	LSD	2	1995	United States
Oak Hill	LSD 51	LSD	3	1996	United States
Pearl Harbour	LSD 52	LSD	4	1998	United States
Raleigh	LPD 1	LPD	1	1962	United States
Vancouver	LPD 2	LPD	2	1963	United States
La Salle	LPD 3	LPD	3	1964	United States
Austin	LPD 4	LPD	1	1965	United States
Ogden	LPD 5	LPD	2	1965	United States
Duluth	LPD 6	LPD	3	1965	United States
Cleveland	LPD 7	LPD	4	1967	United States
Dubuque	LPD 8	LPD	5	1967	United States
Denver	LPD 9	LPD	6	1968	United States
Juneau	LPD 10	LPD	7	1969	United States
Coronado	LPD 11	LPD	8	1970	United States
Shreveport	LPD 12	LPD	9	1970	United States
Nashville	LPD 13	LPD	10	1970	United States
Trenton	LPD 14	LPD	11	1971	United States
Ponce	LPD 15	LPD	12	1971	United States
Svalbard	W303	Icebreaker	1	2001	Norway
Carlskrona	M04	LPD	1	1982	Sweden
Atle	—	Icebreaker	1	1985	Sweden
Oden	—	Icebreaker	1	1989	Sweden
Protecteur	AOR 509	AOR	1	1969	Canada
Preserver	AOR 510	AOR	2	1970	Canada
Albion	L14	LPD	1	2003	United Kingdom
Bulwark	L15	LPD	2	2005	United Kingdom
Largs Bay	L3006	LSD	1	2006	United Kingdom
Lyme Bay	L3007	LSD	2	2007	United Kingdom
Mounts Bay	L3008	LSD	3	2006	United Kingdom
Cardigan Bay	L3009	LSD	4	2006	United Kingdom
Ocean	L12	LPH	1	1998	United Kingdom
Siroco	L9012	LSD	2	1998	France
Mistral	L9013	AAS	1	2006	France
Tonnerre	L9014	AAS	2	2007	France
Dixmude (BPC3)	L9015	AAS	3	2010	France

2.1 Technical Data

Descriptive, technical, and cost data was gathered for each of the ships in the SAS-076 data set. The list of these ship attributes are broken down into the categories as per Table 2. Tables 15 and 16 in Annex **??** detail the technical attributes (categories III to XIV of Table 2) of the 17 ship classes. Table 3 details the attributes as well as the input for HMS Rotterdam and Johan de Witt ships. Attribute units are expressed by either nominal values (e.g., “fixed pitch” (fp), “controlled pitch” (cp), “yes” (Y), “no” (N)), or by numerical units such as meters (m), milimeters (mm), megawatts (MW), knots (kts), hours (hrs), nautical miles (nmi), etc. Unknown or missing data is denoted by “?” entries. For conciseness, undefined technical acronyms appearing in Tables 2 or 3 are listed at the end of the document.

Table 2: Categories of ship data

	Category	Number of Attributes
I	DESCRIPTION	6
II	CONSTRUCTION	8
III	DIMENSIONS	5
IV	PERFORMANCE	8
V	PROPULSION	9
VI	ELECTRICAL POWER GENERATION	3
VII	LIFT CAPACITY	35
VIII	FLIGHT DECK	19
IX	ARMAMENT	13
X	COUNTERMEASURES	5
XI	RADARS / TACAN / IFF / SONARS	13
XII	COMBAT DATA SYSTEMS	1
XIII	WEAPONS CONTROL SYSTEMS	1
XIV	OTHER CAPABILITIES	7
XV	COST DATA	3
	Total:	136

Table 3: Complete list of ship data for the Rotterdam and Johan de Witt LPDs

Data Category & Element	Rotterdam LPD	Johan de Witt LPD
I. DESCRIPTION		
a. Name	Rotterdam	Johan de Witt
b. Nation	Netherlands	Netherlands
c. Number	L800	L801
d. Type	Landing Platform Dock	Landing Platform Dock
e. Rank in class	1	1
f. Vessel type (Military / Civilian)	Military	Military
II. CONSTRUCTION		
a. Laid down	1/25/1996	6/18/2003
b. Launched	2/22/1997	5/13/2006
c. Commissioned	4/18/1998	11/30/2007
d. Shipyard	Royal Schelde	Royal Schelde
e. City	Vlissingen	Vlissingen
f. Country	Netherlands	Netherlands

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Data Category & Element	Rotterdam LPD	Johan de Witt LPD
g. Continent	Europe	Europe
h. Built to civilian classification society standards?	Y	Y
III. DIMENSIONS		
a. Length (m)	162.2	176.35
b. Beam (m)	25	25
c. Draught (m)	5.9	5.9
d. Displacement (tonnes) Light load	8410	11560
e. Displacement (tonnes) Full load	12750	16680
IV. PERFORMANCE		
a. Top speed (kts)	19	19
i. Range: Total distance (nmi)	6000	10000
ii. Range: Economical speed (kts)	12	12
iii. Range: Sailing time (hours)	500	833
b. Endurance (days)	42	42
c. Crew: complement	113	146
i. Officers	13	17
ii. Non-officers	100	129
V. PROPULSION		
a. Propulsion technology	Electric	Electric
b. Propeller shafts	2	0
i. Shaft propulsion power (MW)	12	0
ii. Propeller type	fixed pitch	N/A
c. Propulsion pods	0	2
i. Total podded propulsion power (MW)	0	11
d. Net propulsion power (MW)	12	11
e. Bow Thrusters	1	2
i. Total thruster power (MW)	1.15	1.8
VI. ELECTRICAL POWER GENERATION		
a. Generators	4	4
i. Total power generation capacity (MW)	14.6	14.4
ii. Generator technology	Diesel	Diesel
VII. LIFT CAPACITY		
a. Vehicle fuel (litres)	9000	14500
b. Aviation fuel (litres)	284400	306600
c. Fresh water (litres)	263100	329900
d. Bulk cargo space (m^3)	3680	4170
e. Vehicle space (m^2)	720	1770
f. Well deck (Y/N)	Y	Y
i. Length (m)	50	35
ii. Width (m)	14	15
iii. Capacity (m^2)	700	525
iv. LCAC	0	0
v. LCM 6	?	?
vi. LCM 8	4	4
vii. LCU	4	4
viii. LVT	?	?
ix. LCVP	6	6
x. LCPL	?	?
xi. EFV	?	?
g. Cargo/Aircraft Elevator/Lifts	0	0
i. Capacity $\leq$ 5 tonnes	0	0
ii. 5 < capacity $\leq$ 10 tonnes	0	0
iii. 10 < capacity $\leq$ 15 tonnes	0	0
iv. Capacity $\geq$ 15 tonnes	0	0
h. Cranes	1	1
i. Capacity $\leq$ 5 tonnes	0	0
ii. 5 < capacity $\leq$ 10 tonnes	0	0
iii. 10 < capacity $\leq$ 15 tonnes	0	0
iv. 15 < capacity $\leq$ 20 tonnes	0	0
v. 20 < capacity $\leq$ 25 tonnes	1	1
vi. 25 < capacity $\leq$ 30 tonnes	0	0
vii. 30 < capacity $\leq$ 40 tonnes	0	0
viii. 40 < capacity $\leq$ 50 tonnes	0	0
ix. 50 < capacity $\leq$ 60 tonnes	0	0
x. Capacity > 60 tonnes	0	0
i. Berthing (troop capacity): Baseline	611	555
j. Berthing (troop capacity): Surge	100	100
VIII. FLIGHT DECK		
a. Equipped with flight deck? (Y/N)	Y	Y
b. Flight deck length (m)	56	58
c. Flight deck width (m)	25	25
d. Flight deck area (m^2)	1400	1450
e. Helicopter landing spots (maximum number)	2	2

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Data Category & Element	Rotterdam LPD	Johan de Witt LPD
i. Merlin / Sea King	2	2
ii. NH 90 / Lynx / Puma / Cougar	2	2
iii. CH-46E Sea Knight	?	?
iv. CH-53 Sea Stallion	?	?
v. MV-22 Osprey	?	?
f. Chinook capable (Yes/No)	N	Y
g. Equipped with hangar? (Y/N)	Y	Y
h. Hangar size (m^2)	475	560
i. Helicopters supported (largest total number)	6	6
i. Merlin / Sea King	4	4
ii. NH 90 / Lynx / Puma / Cougar	6	6
iii. CH-46E Sea Knight	?	?
iv. CH-53 Sea Stallion	?	?
v. MV-22 Osprey	?	?
IX. ARMAMENT		
a. Guns (calibre $\geq$ 75mm)	0	0
b. Guns (50mm $\leq$ calibre < 75mm)	0	0
c. Guns (30mm $\leq$ calibre < 50mm)	0	0
d. Guns (20mm $\leq$ calibre < 30mm)	0	0
e. 30mm CIWS emplacements (Goalkeeper)	2	2
f. 20mm CIWS emplacements (Phalanx)	0	0
g. Machine guns (12.7mm)	8	4
h. Machine guns (7.62mm)	0	0
i. SSM launchers	0	0
j. SAM launchers	0	0
k. Number of torpedoes carried	0	0
l. Torpedo tubes	0	0
m. Torpedo launchers	0	0
X. COUNTERMEASURES		
a. Chaff launchers	4	4
b. Torpedo decoys	1	1
c. Other systems	0	0
d. Number of ESM systems	1	1
e. Number of ECM systems	1	1
XI. RADARS / TACAN / IFF / SONARS		
a. Total radar systems mounted	4	5
i. A-band	0	0
ii. B-band	0	0
iii. C-band	0	0
iv. D-band	0	0
v. E-band	1	2
vi. F-band	1	2
vii. G-band	0	1
viii. H-band	0	0
ix. I-band	3	3
x. J-band	0	0
b. Number of TACAN/IFF systems mounted	1	1
c. Number of distinct sonar systems mounted	0	0
XII. COMBAT DATA SYSTEMS		
a. Number of distinct systems	2	2
XIII. WEAPONS CONTROL SYSTEMS		
a. Number of distinct systems	1	1
XIV. OTHER CAPABILITIES		
a. Equipped with hospital? (Y/N)	Y	Y
i. Number of beds	10	7
ii. Operating rooms	1	1
iii. X-Ray facility (Y/N)	Y	Y
b. Dental capability (Y/N)	Y	Y
c. Command/Control facility (Y/N)	Y	Y
d. NBCD Facilities (Y/N)	Y	Y
XV. COST DATA		
a. Base year	?	?
b. Currency	EUR	EUR
c. Development and Production Cost	?	?

2.2 Cost Data

The SAS-076 ship data set includes ship costs expressed in various currencies: Great Britain pound sterling (GBP), U.S. dollars (USD), Canadian dollars (CAD), Norwegian krone (NOK), Swedish kronor (SEK), and Euros (EUR). Costs are also expressed in various then-years[8], ranging from 1952 to 2009. The SAS-054 recommendations for cost normalization of multinational programs are summarized as follows:

[8] Amounts that include the effects of inflation or escalation, and/or reflect the price levels expected to prevail during the year at issue.

1. apply escalation formulae using indices from supplier nations to model changes due to national inflation prior to conversion to other currencies;

2. each nation should apply its own cost inflation model based on applicable data and nation specific economic advice that is pertinent to the particular system; and,

3. use exchange rates between the national currencies as the currency conversion mechanism.

The SAS-076 Task Group followed the SAS-054 guidelines to normalize the ship costs to a common currency and then-year. Various inflation rates were research, and in particular the Task Group was guided by U.S. Naval Sea Systems Command (NAVSEA) representatives who were not aware of any "publicly available total ship cost index that goes back to the 1950s" [6]. The U.S. Bureau of Labour Statistics [7] has a shipbuilding labour index, and there are various materiel indices that are applicable to shipbuilding, but the high-level data gathered in the SAS-076 data set is not detailed enough to compute a weighted overall composite index. Instead, inflation rate sources were obtained as follows:

- The SAS-076 U.S. representative from the Office of the Assistant Secretary of the Navy obtained the Historical Shipbuilding and Conversion, Navy (SCN) Total Obligational Authority Index used within the U.S. NAVSEA[9].

- To inflate the cost figures of ships built within countries of the European Union, the EuroStat Labour Inflation rates [8] specific to each country were applied.

- To inflate the cost of Canadian-built ships, the Defence Research & Development Canada Centre for Operational Research & Analysis Defence Economics Team recommended the Industrial Production Index (IPI) [9].

- Upon consultation with FOI—Swedish Defence Research Agency, the IPI was also used to inflate the cost of the Scandinavian-built ships for which pre-dated the available EuroStat indices.

Respecting the anonymity request of some of the nations, the ship costs cannot be made explicit. For the same reason, the common currency and then-year are not disclosed—all subsequent cost figures are presented using a fictitious notional common currency (abbreviated NCC). Figure 2 illustrates the histogram of the SAS-076 data set costs normalized to NCC.

The SAS-076 Task Group log-transformed the cost of each ship as input to the estimation model. The models, to be presented in detail in Subsections 3.0 and 4.0, output a single predicted ship cost in log-space. This prediction is considered to center a normal distribution whose standard deviation is the standard deviation of the model (also in log space) in estimating the costs of the known ships. As a result of the initial log-transformation of the costs, the uncertainty in the prediction of a ship's cost is presented by a log-normal distribution. The log-normal distribution is a probability distribution of a random variable whose logarithm is normally distributed.

The logarithmic transformation is commonly used for positive data; the log-normal distribution domain of zero to infinity is more suitable for modelling ship costs than a normal distribution which includes the negative domain. Log-transformation is also commonly applied when the data ranges over several orders of magnitude—the SAS-076 data set cost range from 50 to 700 million NCC. The majority of total cost estimates for weapon-system acquisition programs modeled by the United States' Deputy Assistant Secretary of the Navy

[9] Provided under the condition that the indices would not be published.

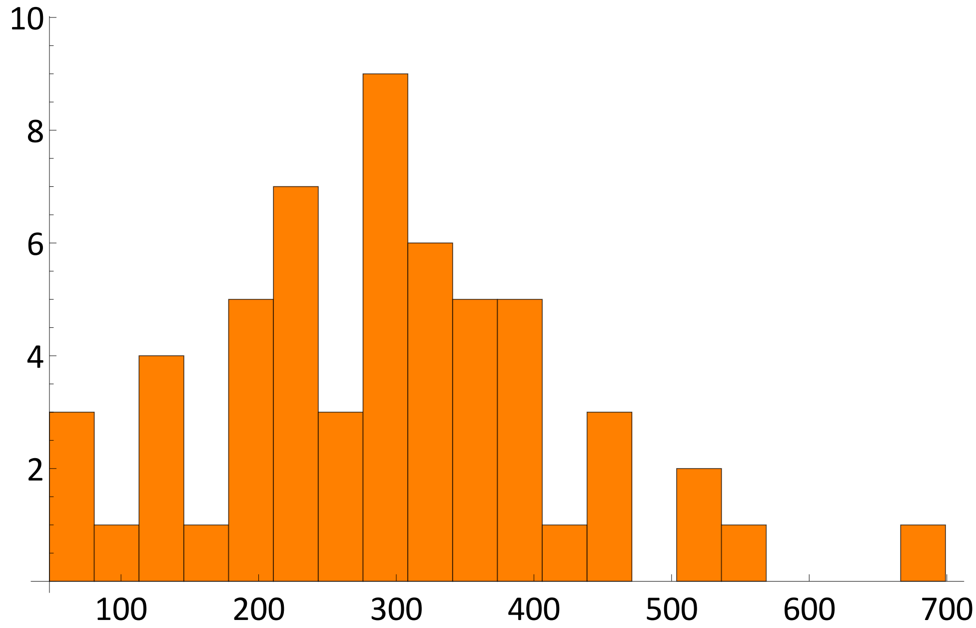

Figure 2: Histogram of normalized costs (millions NCC).

(Cost & Economics) are log-normally distributed and often skewed right [10]. The log-normal distribution is also justifiable choice when a variable is known to be the multiplicative product of many independent random variables each of which is positive (as is usually the case in shipbuilding). Beaulieu *et al.* [11] showed that the distribution of the sum of log-normal random variables can be approximated with a single log-normal distribution.

3.0 PARAMETRIC COST ESTIMATION

Parametric approaches to cost estimation use regression or other statistical methods to develop Cost Estimating Relationships (CERs). A CER is an equation used to estimate a given cost element using an established relationship with one or more independent variables.

There are several advantages of a parametric approach to cost estimation, including:

- it can capture major portions of an estimate quickly and with limited information (as is often the case in early phases of the procurement cycle);
- the CER is objective—it is based on consistent and quantitative inputs;
- once the CER is established it is easy to perform sensitivity analyses (determine the change in cost subject to changes in the independent input variables); and,
- CERs established using regression analyses include standard tests of validity, including a coefficient of correlation indicating the strength of association between the independent variables and the dependent variable in the CER.

A critical consideration in parametric cost estimating is the similarity of the systems in the underlying database, both to each other and to the system which is being estimated. A major disadvantage of typical parametric approaches is that they may not provide low level visibility (cost breakdown) and changes in sub-systems are not reflected in the estimate if they are not quantified via an independent variable.

Traditional ship building CERs are often mathematically simple (e.g. a simple ratio) or involve linear regression analysis (of historical systems or subsystems) on a single parameter (weight, length, density, etc.). However, Miroyannis [12] noted that this is often insufficient and that other cost driving factors must be incorporated to develop estimates of sufficient quality at the preliminary design phase. Furthermore, the relationship between the parameter(s) and cost may not be best expressed in linear form. While the field of regression analysis offers a multitude of alternative approaches (the reader is referred to [13] for further information), linear regression is the most popular and easiest to understand.

The next section describes a novel parametric approach for ship cost estimation that incorporates a multitude of cost driving factors, while remaining a "top down" approach applicable in early design phases of the procurement cycle. It combines features of decision trees with linear regression models to both classify similar ships (based on attributes) and build piece-wise multivariate linear regression models.

3.1 The M5 Model Tree System

In 1992 Quinlan [1] pioneered the M5 system for learning models that predict numeric values. The M5 system combines features of decision trees with linear regression models. M5 model trees are similar to regression trees; a decision tree induction algorithm is used to build an initial tree, recursively splitting the data set based on the value of a chosen splitting attribute. The splitting attribute is selected to minimize the prediction error down each branch. Whereas the nodes of a regression tree each contain a constant value (prediction), each model tree node is a multivariate linear regression model. The attributes defining these regression models are the attributes that are involved in the tree's branching decisions.

Figure 3 depicts a simple example of a M5 model tree. The sub-figure on the left shows a two-dimensional space of independent variables x_1 and x_2. The M5 model tree algorithm splits up the space into regions corresponding to decisions in the tree shown on the right. Linear regression models are fitted to the data in each region. To predict a value for a new instance, the M5 model tree is followed down to a leaf using the instance's

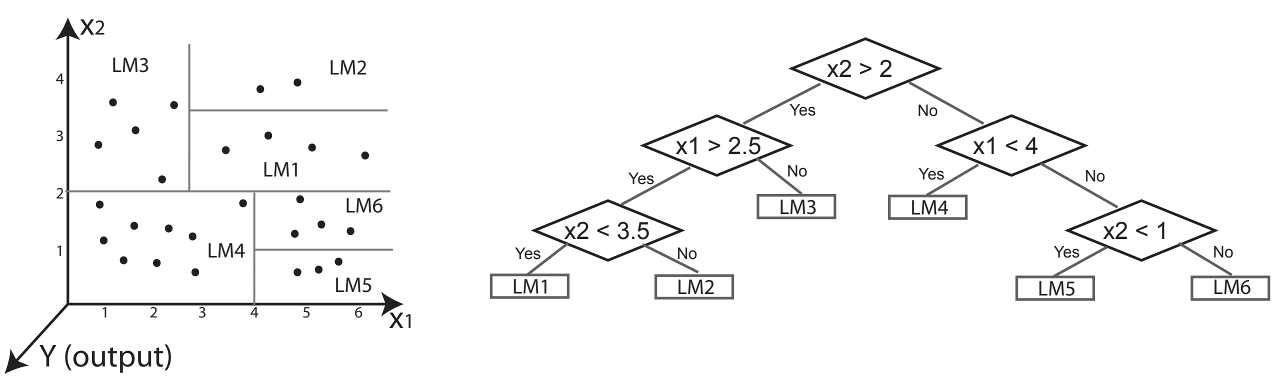

Figure 3: Example M5 model tree.

attribute values to make routing decisions at each node. The leaf contains a linear regression model based on a subset of the attributes, and this is evaluated for the new instance to output a predicted value.

The following paragraph synthesizes the M5 model tree algorithm. Full details are exposed in Annex **??**. The M5 model tree algorithm has four parts to it. In the first part, a decision tree is constructed using the same procedure as for regression trees. The tree is constructed recursively by splitting the training set per attribute value chosen to minimize error in estimation. In the second part, the algorithm constructs multivariate linear models at each node of the model tree using only the attributes that are referenced by tests somewhere in the subtree of this node. These linear models are further simplified by eliminating parameters to minimize the estimated error (accuracy of the model on unseen cases). Part three of the algorithm applies a tree pruning routine which eliminates subtrees of a node if the estimation error is higher in the lower branches than the estimation error when using the node's internal regression model. Finally, a smoothing process, with the goal of improving prediction accuracy, is employed to ensure that the linear regression models of adjacent leaves are continuous and smooth. This process is particularly effective when some of the linear regression models are constructed from few training cases.

3.1.1 Discussion

Regression trees are more accurate than straightforward linear regression, but the trees are often cumbersome and difficult to interpret [14]. Model trees are more sophisticated than regression trees as they approximate continuous functions by linear "patches"—M5 model trees are analogous to piecewise linear functions. M5 model trees have an advantage over regression trees with respect to compactness and prediction accuracy due to the ability of model trees to exploit local linearity in the data. Regression trees will not predict values lying outside the range of learned training cases, while M5 model trees can extrapolate. The M5 model tree algorithm is optimized to both learn known cases and predict unknown cases. The trees are also smaller, easier-to-understand, and their average error values on the training data are lower.

M5 model trees tackle the difficulties in considering a multitude of cost driving factors; they determine the right set of independent variables (ship attributes) by construction. The effect of the M5 system is somewhat similar to the use of indicator variables in standard linear regression analysis, with the key difference being that appropriate indicators are identified and included based on an optimization algorithm.

M5 model trees have been shown to excel even when limited data is available [15] or learn efficiently from large data sets. They can handle data sets which include systems with notable differences, missing data, and noise (as is the case for the SAS-076 ship data set). The decision tree can branch on any variable type: nominal (e.g., military vs. non-military) or numeric (e.g., tonnage less than 15000 or greater than 15000).

The use of M5 model trees for numeric prediction has increased since comprehensive descriptions, implementations, and refinements of Quinlan's method became available [15–19]. Recently Chen [20] discussed the benefits of the system for estimating the cost of software development.

Neural networks are commonly used for predicting numeric quantities, but suffer from the disadvantage of producing opaque structures that mask the nature of the solution. Their arbitrary internal representation means that there can be variations between networks trained on the same data. In comparison, the M5 system is transparent and the model tree construction is repeatable. The final tree and linear regression models are straightforward and clear.

3.2 Application to SAS-076 Ship Data Set

An easy-to-use implementation of Quinlan's M5 model tree is available as part of the WEKA project [21]. Witten and Frank's textbook [14] provides documentation on both the theory and implementation (data formatting, execution, etc.) of the algorithm. The descriptive attributes (I.e), (I.f), (II.h) (as per Table 2), the complete set of technical attributes, and a normalized cost attribute for each of the ships in the SAS-076 data set was used as input to the M5 model tree algorithm. Using WEKA[10], the construction of the M5 model tree for the ship database of 57 ships each with 123 attributes (7011 elements) took less than a second of computation on an Intel(R) 2.4GHz computer with 4GB RAM.

Figure 4 shows the resulting M5 model tree. The root of the decision tree splits the ships in two based on the number of air-cushioned landing craft (LCAC) that the ship is designed to carry (it should be noted that this split also groups all ships void of a well deck). Internal nodes of the tree further split the data set on attributes such as the number (#) of torpedo decoy systems on board, the ship's rank in class, the maximum number of helicopters supported, the ship's length, and the ship's range in terms of total distance in nautical miles. The tree branches out to nine leaves where nine corresponding linear regression models are fitted. The regression models are presented in Table 4. In addition to the ship attributes used in the decision tree for branching, the linear regression models use the ship's range in terms of total sailing time in hours. The linear regression models output the log-transformed (decadic) cost of a ship. The individual linear regression models are mostly intuitive: the cost of a ship increases as the length or the number of LCAC supported or number of torpedo decoy systems increase(s). The regression models also predict a shipbuilding learning curve as the cost of constructing a ship decreases as a function of the ship's rank in class. The negative coefficient for a ship's range (sailing time) in the regression models is counter-intuitive. It seems unlikely that a ship will cost less as its range increases. The SAS-076 ship data explains this anomaly: the median ship range (sailing time) of the ships captured in the SAS-076 ship data set is 444 hours and the mean is 616 hours. Only 6 of the 57 ships have a range greater than 770 hours, these are the U.S. Anchorage class LSDs and Sweden's Oden icebreaker—their sailing time range is between 3-5 times the median. The Anchorage class LSD costs and the Oden icebreaker cost are relatively low (in comparison to the other SAS-076 ships). The combination of these low costing ships and outlying sailing time ranges provides a mathematical explanation for the negative coefficient of the sailing time range in the regression models. The M5 model can be potentially adjusted in an attempt to remove such anomalies by disabling the particular attribute (sailing time), however there is no guarantee that the regenerated model will not substitute this attribute with another, also allocated a negative coefficient. Similarly, removing the instances (e.g., Oden and Anchorage class LPDs) from the data set provides no guarantees. Rather than subjectively diminishing the data set, SAS-076 recommends noting the anomalies and discussing them as part of the results.

Table 5 provides the minimum, median, mean, and maximum values found in the SAS-076 ship data set for the attributes used by the M5 model. Table 6 shows the classification of the SAS-076 ships by the M5 model tree.

Figure 5 plots the actual ship costs vs. the costs predicted by the M5 model tree. The worth of a regression-based model is measured by the coefficient of correlation, the quantity that gives the quality of a least squares fitting to the original data. Let x_i be the actual cost of ship i and y_i the predicted cost (using the M5 model tree), then the coefficient of correlation, R, of the M5 system is calculated as

$$R = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - (\sum x_i)^2}\sqrt{n\sum y_i^2 - (\sum y_i)^2}}, \tag{1}$$

where $n = 57$, the number of ships in the data set, and each of the sums are over these 59 ships. By design R can range from -1 to $+1$ with $R = 1$ indicating a perfect positive linear correlation. A correlation greater than 0.8 is generally described as strong [13]. The value R^2, known as the coefficient of determination, is a

[10] The program's default parameters for the M5 model tree algorithm were used.

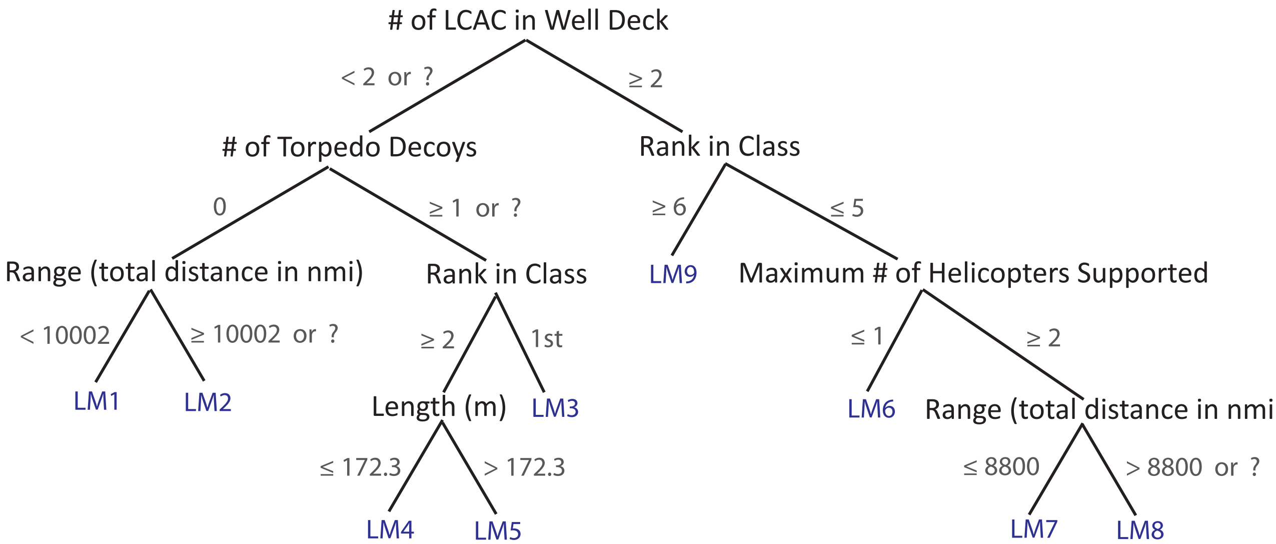

Figure 4: M5 model tree applied to the NATO RTO SAS 076 ship data set.

measure of how well the regression line represents the data—it is a measure determining how certain one can be in making predictions from the model. R^2 is also the ratio of the explained variation (by the model) to the total variation of the data set. The measures of worth of the M5 model tree for predicting ship costs are a strong $R = 0.96$ and $R^2 = 0.92$. The coefficient of determination indicates that 92% of the total variation in the ship costs can be explained by the linear relationships described by the M5 model tree linear regression equations. The remaining 8% of the total variation remains unexplained.

Another useful indicator is the mean absolute percent error, as it quantifies the the amount by which the estimated cost differs from the actual cost. The mean absolute percent error is computed as as follows:

$$\frac{1}{57}\sum_{i=1}^{i=57}\frac{|x_i - y_i|}{x_i} \tag{2}$$

The mean absolute percent error for the M5 model tree applied to the SAS-076 ship data set is 12%. The standard deviation, indicating the variation that M5 model tree predictions have from the actual costs, is computed as

$$\sqrt{\frac{\sum_{i=1}^{57}(x_i - y_i)^2}{57}}, \tag{3}$$

for a value of 46.4 million NCC. Mean absolute percent errors and standard deviations specific to the individual M5 model tree linear regression models are shown in Table 7. For the purpose of determining the standard deviation of a M5 model tree output prediction, the standard deviation over all the training data is more reflective of the M5 system than just the standard deviation of the training cases reaching the particular leaf node used for the prediction. By M5 model tree construction, each of the training cases influence the structure of the final model tree.

Table 4: M5 model tree linear regression models

LM1		LM2	
Log(Cost) =	7.4297	Log(Cost) =	7.4208
	- 0.0112 × rank in class		- 0.0112 × rank in class
	+ 0.0045 × length (m)		+ 0.0045 × length (m)
	- 0.0002 × range (sailing time in hrs)		- 0.0002 × range (sailing time in hrs)
	+ 0.0445 × # of LCAC in well deck		+ 0.0445 × # of LCAC in well deck
	+ 0.1104 × # of torpedo decoys		+ 0.1104 × # of torpedo decoys
LM3		LM4	
Log(Cost) =	7.6222	Log(Cost) =	7.7567
	- 0.0167 × rank in class		- 0.0172 × rank in class
	+ 0.0041 × length (m)		+ 0.0032 × length (m)
	- 0.0002 × range (sailing time in hrs)		- 0.0002 × range (sailing time in hrs)
	+ 0.0445 × # of LCAC in well deck		+ 0.0445 × # of LCAC in well deck
	+ 0.0659 × # of torpedo decoys		+ 0.0659 × # of torpedo decoys
	+ 0.00001 × range (distance in nm)		
LM5		LM6	
Log(Cost) =	7.7912	Log(Cost) =	7.9846
	- 0.0170 × rank in class		- 0.0245 × rank in class
	+ 0.0030 × length (m)		+ 0.0038 × length (m)
	- 0.0002 × range (sailing time in hrs)		- 0.0003 × range (sailing time in hrs)
	+ 0.0445 × # of LCAC in well deck		+ 0.0300 × # of LCAC in well deck
	+ 0.0659 × # of torpedo decoys		+ 0.0343 × # of torpedo decoys
LM7		LM8	
Log(Cost) =	8.1461	Log(Cost) =	8.3575
	- 0.0361 × rank in class		- 0.0312 × rank in class
	+ 0.0035 × length (m)		+ 0.0024 × length (m)
	- 0.0003 × range (sailing time in hrs)		- 0.0003 × range (sailing time in hrs)
	+ 0.0300 × # of LCAC in well deck		+ 0.0300 × # of LCAC in well deck
	+ 0.0343 × # of torpedo decoys		+ 0.0343 × # of torpedo decoys
LM9			
Log(Cost) =	8.3001		
	- 0.0221 × rank in class		
	+ 0.0020 × length (m)		
	- 0.0003 × range (sailing time in hrs)		
	+ 0.0300 × # of LCAC in well deck		
	+ 0.0343 × # of torpedo decoys		

Table 5: Statistics of attributes used in the M5 model tree linear regression models.

Attribute	Minimum	Median	Mean	Maximum
Rank	1	3	3.68	12
Length	103.7	173.8	170.3	203.4
Range (sailing time)	385	444	616	2308
# LCAC	0	2	2	4
# Torpedo decoys	0	0	2	8
# of helicopters supported	0	5	6	18

Table 6: M5 model tree classification of SAS-076 ships.

LM1	LM2	LM3	LM4	LM5	LM6	LM7	LM8	LM9
Svalbard	Carlskrona	Thomaston	Plymouth Rock	Lyme Bay	Anchorage	Whidbey Island	Raleigh	Tortuga
Protecteur	Atle	Largs Bay	Fort Snelling	Mounts Bay	Portland	Germantown	Vancouver	Rushmore
Preserver	Oden	Ocean	Point Defiance	Cardigan Bay	Pensacola	Fort McHenry	La Salle	Ashland
			Spiegel Grove		Mount Vernon	Gunston Hall	Mistral	Denver
			Alamo		Fort Fisher	Comstock	Tonnerre	Juneau
			Hermitage		Harpers Ferry	Austin	Dixmude (BPC3)	Coronado
			Monticello		Carter Hall	Ogden		Shreveport
			Siroco		Oak Hill	Duluth		Nashville
					Pearl Harbour	Cleveland		Trenton
						Dubuque		Ponce
						Albion		
						Bulwark		

Table 7: Mean absolute percent errors of known instances and standard deviations per individual M5 model tree linear models.

	LM1	LM2	LM3	LM4	LM5	LM6	LM7	LM8	LM9
Mean % error:	22%	27%	17%	3%	33%	12%	14%	8%	6%
Standard deviation	24.3M	16.9M	53.0M	6.4M	45.6M	43.4M	78.0M	39.3M	24.3M
# of instances:	3	3	3	8	3	9	12	6	10

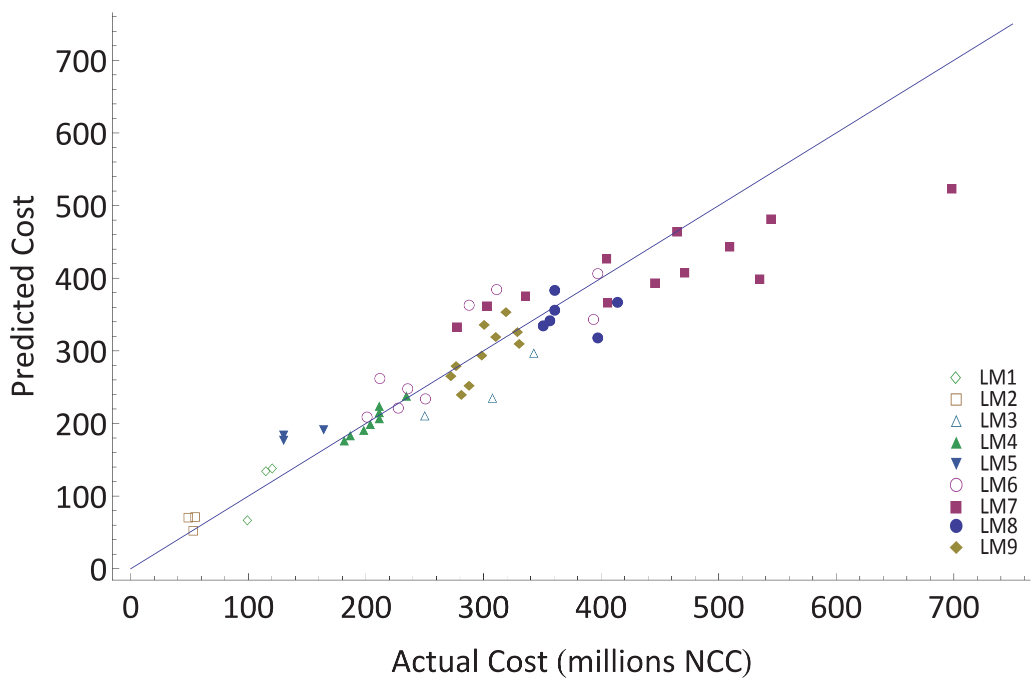

Figure 5: M5 model tree: correlation plot of actual vs. predicted ship costs (millions NCC).

3.2.1 Comparison to Linear Regression Models

The best CER returned by applying simple linear regression on the SAS-076 data set[11] is

$$Log_{10}(cost) = 6.95 + 0.01 \times \text{ length of ship (in meters)}, \tag{4}$$

with an R value of 0.75 ($R^2 = 0.56$). Applying multiple linear regression with a greedy attribute selection method (step through the attributes removing the one with the smallest standardized coefficient until no improvement is observed in the estimate of the error given by the Akaike information criterion [22]), yields the CER

$$\begin{aligned} Log_{10}(cost) = 5.7368 &- 0.0224 \times \text{ rank in class} \\ &+ 0.0121 \times \text{ length (in meters)} \\ &+ 0.0338 \times \text{ beam (in meters)} \\ &+ 0.1071 \times \text{ draught (in meters)} \\ &- 0.0001 \times \text{ full load displacement (in tonnes)} \\ &+ 0.0012 \times \text{ crew size} \\ &- 0.0876 \times \text{ number of propeller shafts} \\ &- 0.0239 \times \text{ number of guns of calibre } \geq 75, \end{aligned} \tag{5}$$

with an R value of 0.92 ($R^2 = 0.85$). While the CER produced by applying simple linear regression is straightforward to understand, the negative coefficient signs of the multiple linear regression CER makes its interpretation non-trivial—detailed analysis of the input data is required. For comparison to the M5 model tree, the straightforward linear regression estimates for HMS Rotterdam and Johan de Witt LPDs are presented in Section 5.0.

The results presented in Table 7 show that linear regression model LM7 contributes greatest to the standard deviation. Further analysis revealed that LM7 models the nine highest costing ships, all over 400 million NCC. In eight of these cases, LM7 underestimates the actual cost. By the piece-wise linear M5 model tree construction, LM7 is influenced by the adjacent linear regression models LM6 and LM8. To evaluate the degree of this influence, a separate multiple linear regression model was fitted to the ships reaching the LM7 leaf using the same five ship attributes as LM7. The resulting CER is as follows:

$$\begin{aligned} Log_{10}(cost) = 8.6376 &- 0.0651 \times \text{ rank in class} \\ &+ 0.0637 \times \text{ number of LCAC.} \end{aligned} \tag{6}$$

with an R value of 0.95 ($R^2 = 0.90$), mean absolute percent error of 7% and a standard deviation of 34.8 million NCC. This result indicates that it is indeed possible to derive better models for subsets of the data. This does not depreciate the M5 model tree algorithm whose strength is its optimization in predicting unknown cases (rather than simply memorizing the known). Using the linear regression model of Equation 6 in place of LM7 would leave adjacent linear models LM6, LM7, and LM8 sharply discontinuous. The M5 system applies a smoothing process (see Annex **??**) to construct piece-wise linear regression models[12].

[11] Nominal attributes and attributes for which data was missing was omitted.

[12] Experiments by Wang and Witten [15] show that this smoothing substantially increases the accuracy of predictions of unseen cases.

4.0 COST ESTIMATION BY ANALOGY

Cost estimation by analogy is typically accomplished by forecasting the cost of a new system based on the historical cost of similar or analogous system [23]. There must be a reasonable correlation between the new and historical system. The cost of the historical system is adjusted by undertaking a technical evaluation of the differences between the systems, deducting the cost of components that are not comparable to the new design and adding estimated costs of the new components. Subject matter experts are required to make a subjective evaluation of the differences between the new system of interest and the historical system. Subjectively chosen complexity factors are often used to adjust the analogous system's cost to produce an estimate. The credibility of the estimate for the new system may be undermined if the adjustment factors are not substantiated—this is a key disadvantage of the traditional analogy method.

In the next section hierarchical cluster analysis is used for a novel cost estimation by analogy approach that is void of the subjectivity inherent (of the traditional approach) in quantifying the cost of the technical and other differences between the historical system and the new system. The approach also considers multiple analogous systems rather than just one.

4.1 Hierarchical Cluster Analysis

Hierarchical cluster analysis is a data mining approach that facilitates cost estimation by analogy by identifying the systems that are the "nearest neighbours" to the new system. Hierarchical cluster methods produce a hierarchy of clusters grouping similar items together: from small clusters of very similar items to large clusters that include more dissimilar items. In particular, agglomerative hierarchical methods work by first finding the clusters of the most similar items and progressively adding less similar items until all items have been included into a single large cluster. Hierarchical agglomerative cluster analysis begins by calculating a matrix of distances among systems expressing all possible pairwise distances among them. Initially each system is considered a group, albeit of a single item. Clustering begins by finding the two systems that are most similar, based on the distance matrix, and merging them into a single group. The characteristics of this new group are based on a combination of the systems in that group. This procedure of combining two groups and merging their characteristics is repeated until all the systems have been joined into a single large cluster.

Hierarchical cluster analysis is a useful means of observing the structure of the data set. The results of the cluster analysis are shown by a dendrogram (tree), which lists all of the samples and indicates at what level of similarity any two clusters were joined. The x-axis is a measure of the similarity or distance at which clusters join. The resulting clustering can be used to estimate the cost of a new system by taking a weighted average of the cost of historical systems based on the relative distances between the new system and the historical systems.

4.2 Application to SAS-076 Ship Data Set

Using the SAS-076 ship data set, hierarchical clustering is used to define a ship distance function which takes as input ship attributes for a pair ships and outputs a single value indicating the distance, or similarity, between the two ships. Formally, define

$$d_{ijk} = \text{ distance between ship } i \text{ and } j \text{ with respect to attribute } k. \tag{7}$$

For numeric attributes, d_{ijk} is normalized to lie in the $[0,1]$ range with $d_{ijk} = 1$ indicating that ships i and j lie at opposite ends of the observed spectrum for attribute k (e.g., shortest and longest length ships), and $d_{ijk} = 0$ indicating that the ships are the same with respect to attribute k. For nominal attributes, d_{ijk} is binary—set to 0 if ship i and j are the same with respect to attribute k, and 1 if they are not.

A variety of distance metrics can be used to calculate similarity of two ships based on the attribute distances d_{ijk}. Using a simple Euclidean distance metric, the aggregate distance between two ships i and j, is expressed as

$$d_{ij} = \sqrt{\sum_{k \in A} d_{ijk}^2} \tag{8}$$

where A is the subset of attributes considered. Figure 7 illustrates the dendrogram resulting from the hierarchical clustering of ships using a the simple distance function (equation (8)) and a set of 123 attributes including descriptive attributes (I.e), (I.f), (II.h) and the complete set of technical attributes as per Table 2. The dendrogram indicates that HMS Rotterdam is best grouped with HMS Johan de Witt. Both Netherlands LPDs are then clustered with the French Mistral class AASs, namely the Mistral, Tonnerre, and Dixmude. The next closest ship to this agglomerative cluster is the United Kingdom's Ocean LPH, and so on.

Computing the distances between all pairs of ships using equation (8), the cost of a ship i can be estimated by computing the weighted-average cost of the other ships. Let C_j be the known cost of ship j, then

$$\tilde{C}_i = \sum_{j \neq i} \frac{C_j}{d_{ij}^2} \cdot \frac{1}{\sum_{j \neq i} \frac{1}{d_{ij}^2}} \tag{9}$$

is the estimated cost of ship i. Figure 6 plots the actual ship costs, C_i, vs. the costs predicted, $\tilde{C}_i$, by the analogy method using hierarchical clustering based on a simple distance metric. The measures of worth of the analogy method via hierarchical clustering analysis (simple distance metric) for predicting ship costs are $R = 0.48$ (coefficient of correlation as calculated by Equation 1) and $R^2 = 0.23$. The mean absolute percent error is 49% and the standard deviation of 112 million NCC. The approach does poorly in learning the known ship costs.

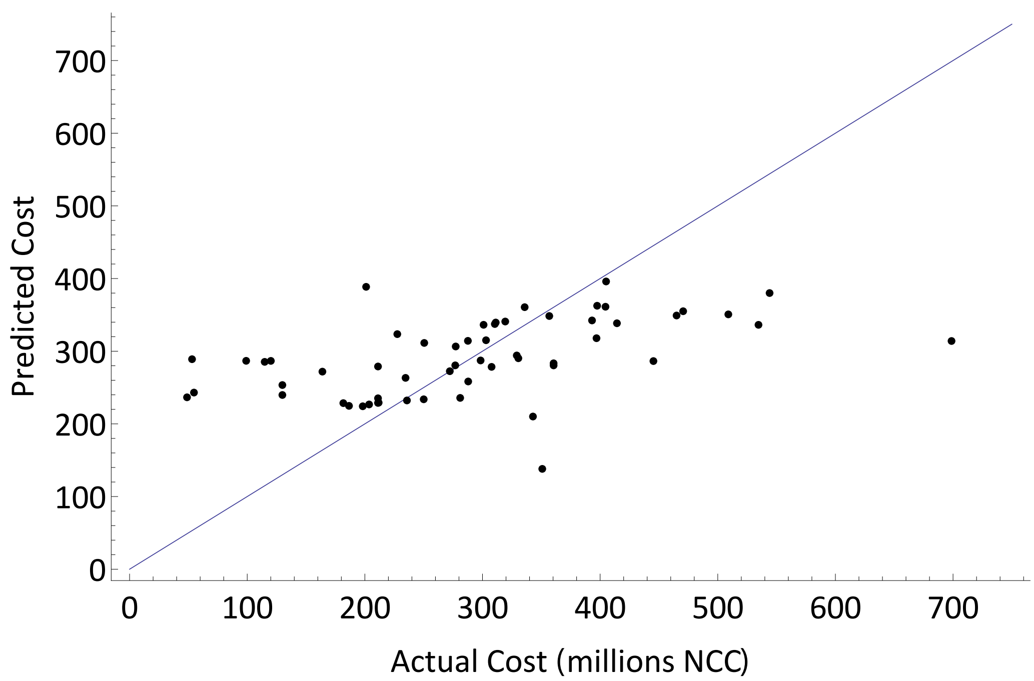

Figure 6: Hierarchical clustering with simple distance function: correlation plot of actual vs. predicted ship costs (millions NCC).

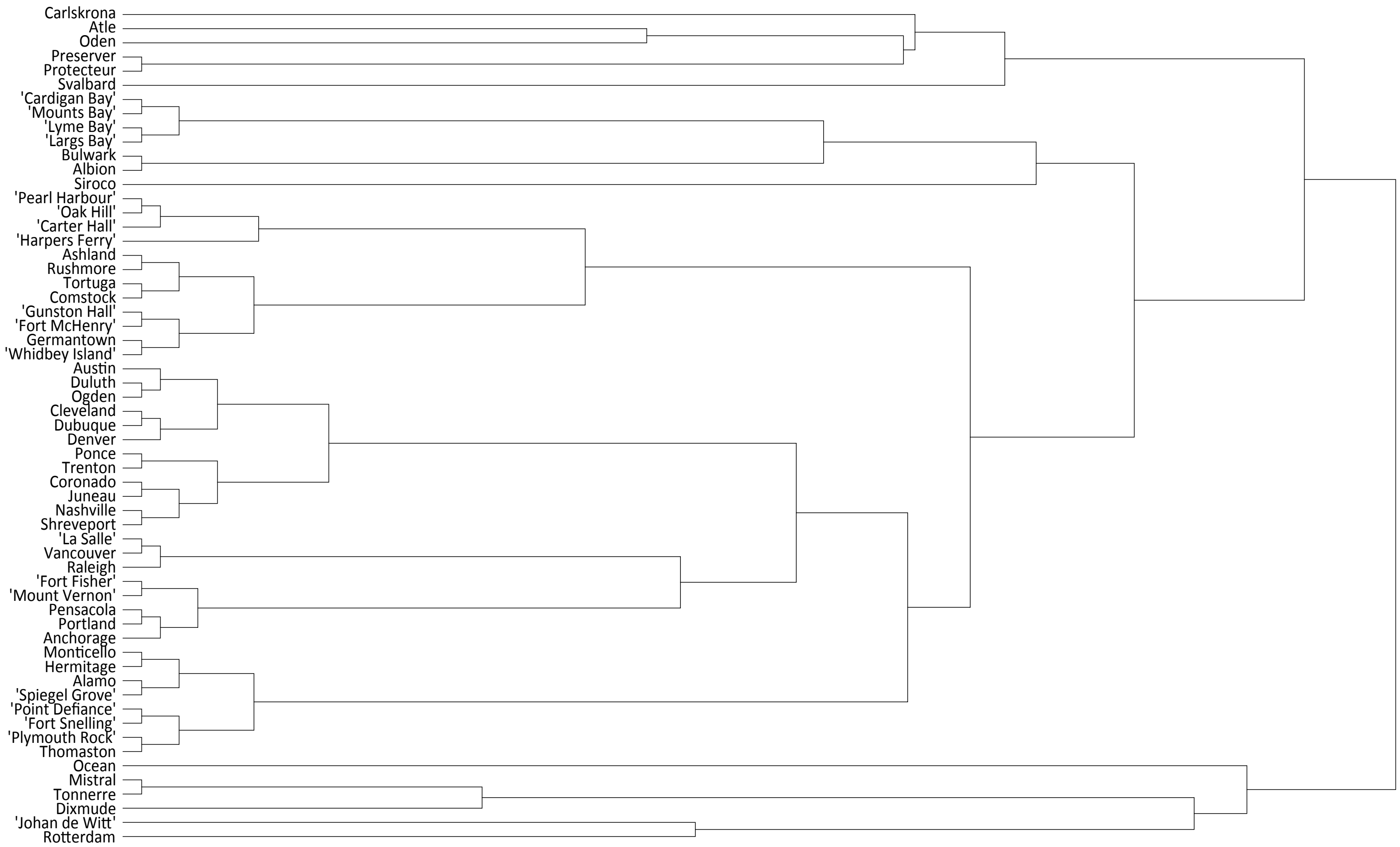

Figure 7: Dendrogram illustrating the arrangement of the clusters produced by the hierarchical clustering of ships (simple distance function).

An assumption in the above approach is that all attributes are of equal importance; the (normalized) differences or similarities for each attribute contribute equally to the measure of similarity between ships. To potentially improve the predictive capability of the method, attribute weights are defined. Let

$$w_k = \text{ weight of attribute } k. \tag{10}$$

Using a weighted Euclidean distance metric, the aggregate distance between two ships i and j, is expressed as

$$\hat{d}_{ij} = \sqrt{\sum_{k \in A} (w_k \cdot d_{ijk})^2}, \tag{11}$$

where $\sum_{k \in A} w_k = 1$ and $w_k \geq 0$ for all k. As before, let C_j be the known cost of ship j, then

$$\hat{C}_i = \sum_{j \neq i} \frac{C_j}{\hat{d}_{ij}^2} \cdot \frac{1}{\sum_{j \neq i} \frac{1}{\hat{d}_{ij}^2}} \tag{12}$$

is the estimated cost of ship i using weighted attributes. The optimal allocation of weights is determined by minimizing the prediction error for the known ships,

$$\text{minimize} \sum_{i=1}^{57} \left(C_i - \hat{C}_i\right)^2. \tag{13}$$

The resulting mathematical optimization is a non-linear convex program. With the full set of attributes used previously, $|A| = 123$, the mathematical program was too computationally intensive to solve in reasonable time using Wolfram *Mathematica*© on a Intel(R) 2.4GHz computer with 4GB RAM. To reduce the dimensionality of the problem, a smaller subset of attributes was selected. While there are numerous attribute selection algorithms (see [14]), principal component analysis (PCA), a tool in exploratory data analysis and for making predictive models, was used. PCA involves a mathematical procedure that transforms a number of possibly correlated variables into a smaller number of uncorrelated variables called principal components. The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible[13].

The WEKA software tool [21] was used to perform PCA. The ship data set consisting of 123 attributes (as used with the simple distance function) was reduced to a set of 16 macro-attributes accounting for 95% of the original set's variability. Table 8 lists the macro-attributes and the respective percentage of data variability (cumulative) each accounts for.

Each macro-attribute is a linear combination of the original attributes. For example, macro-attribute A2 is

[13] PCA involves the calculation of the eigenvalue decomposition of a data covariance matrix. Dimensionality reduction is accomplished by choosing enough eigenvectors to account for some percentage of the variance in the original data. PCA can be thought of as revealing the internal structure of the data in a way which best explains the variance in the data. If a multivariate dataset is visualized as a set of coordinates in a high-dimensional data space (1 axis per variable), PCA supplies the user with a lower-dimensional picture, a "shadow" of this object when viewed from its (in some sense) most informative viewpoint.

Table 8: Principal component analysis results

Macro-Attribute	% of Data Variability Accounted for Proportion	Cumulative
A1	17%	17%
A2	12%	29%
A3	11%	41%
A4	9%	49%
A5	8%	57%
A6	7%	64%
A7	6%	69%
A8	5%	74%
A9	4%	78%
A10	3%	81%
A11	3%	85%
A12	3%	88%
A13	3%	90%
A14	2%	92%
A15	2%	94%
A16	1%	95%

$$\begin{aligned} A2 = {} & 0.204 \times \text{length} \\ & + 0.196 \times \text{beam width} \\ & + 0.183 \times \text{vehicle space} \\ & + 0.18 \times \text{\# of expeditionary fighting vehicles} \\ & + 0.165 \times \text{1 if has a well deck, otherwise 0} \\ & + 0.165 \times \text{width of the well deck} \\ & + 0.164 \times \text{length of the well deck} \\ & + 0.159 \times \text{\# of large personnel landing craft} \\ & + 0.156 \times \text{\# of Chinook helicopters supported} \\ & + 0.155 \times \text{full load displacement} \\ & + 0.153 \times \text{\# of combat data systems} \\ & + 0.150 \times \text{light load displacement} \\ & + 0.144 \times \text{well deck capacity} \\ & + 0.143 \times \text{\# of elevators} \\ & + 0.142 \times \text{vehicle fuel capacity} \\ & \text{etc.} \end{aligned} \tag{14}$$

(Only the top 15 attributes—in terms of PCA coefficient size—are enumerated in Equation 14.) Attempting to find solutions to the mathematical program (13) with $|A| = 16$ macro-attributes resulted in memory overflow. Using the top ten macro-attributes, accounting for 80% of the original data set's variance, an optimal solution for the macro-attribute weights was determined. The weights are listed in Table 9. Only macro-attributes A1, A2, A4, and A8 have non-zero weights. This is a typical extreme output of mathematical optimization software. There may exist other optimal solutions with other non-zero macro-attributes weights. Annex **??** shows the resulting top ten macro-attributes for the 57 SAS-076 ships as well for HMS Rotterdam and Johan de Witt LPDs.

Table 9: Optimal macro-attribute weights for cost estimation by hierarchical clustering

Attribute	Weight
A1	0
A2	0.452
A3	0
A4	0
A5	0.334
A6	0
A7	0
A8	0
A9	0
A10	0.214

The hierarchical cluster analysis using the weighted distance function on the top ten macro-attributes determined by PCA is visualized in Figure 8. The figure illustrates the resulting dendrogram indicating that HMS Rotterdam LPD is grouped with the United Kingdom's Albion class LPDs and Largs Bay class LSDs, followed by France's Siroco LSD, etc. HMS Johan de Witt LPD is clustered with Sweden's Svalbard icebreaker, France's Mistral class AAS, United Kingdom's Ocean LPH, and so on[14].

[14] As expected, ships within the same class (but different rank) are closely grouped together.

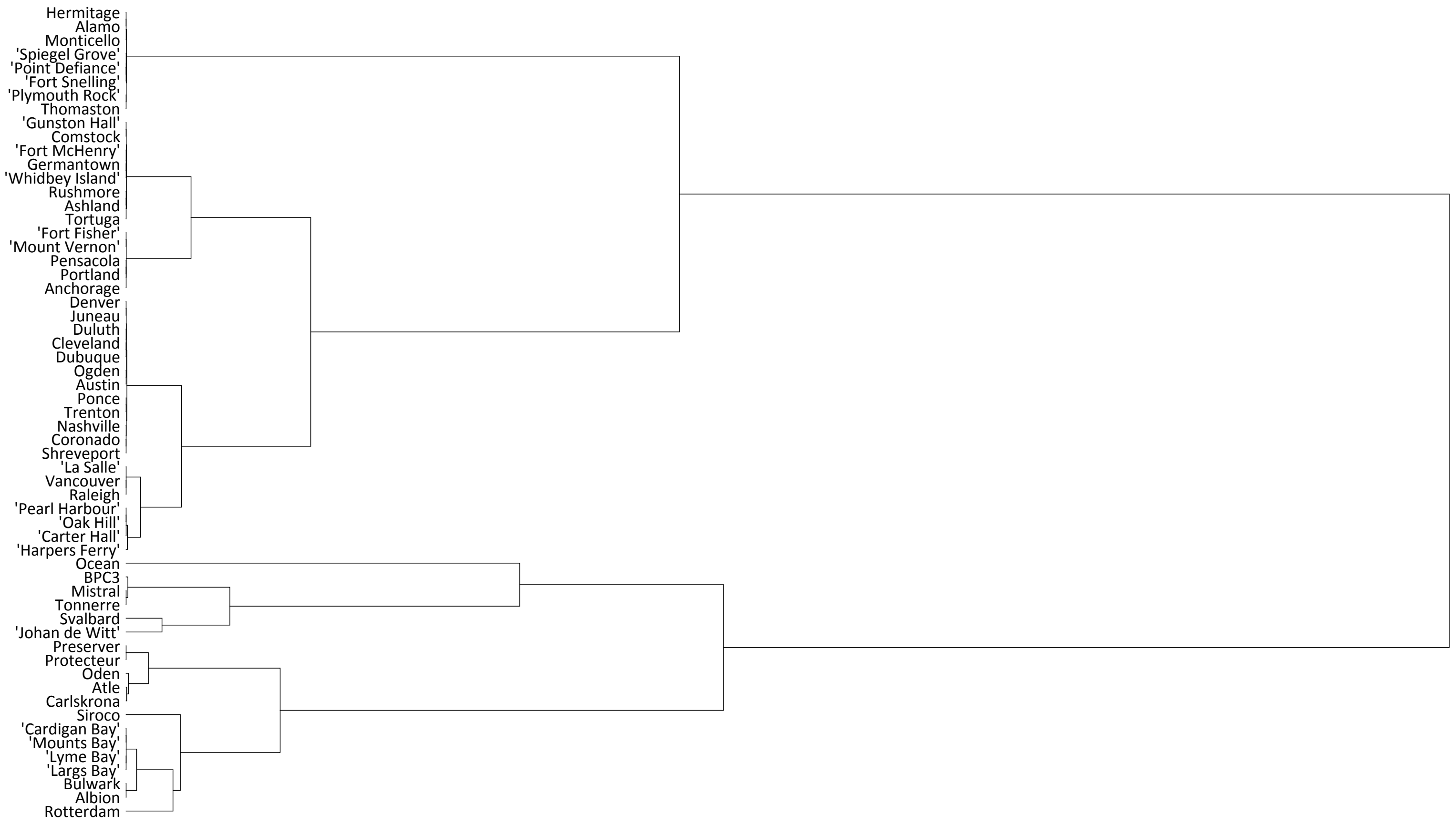

Figure 8: Dendrogram illustrating the arrangement of the clusters produced by the hierarchical clustering of ships (weighted distance function).

Figure 9 plots the actual ship costs, C_i, vs. the costs predicted, $\hat{C}_i$, by the analogy method using hierarchical clustering based on a weighted distance metric. The measures of worth of the analogy method via hierarchical clustering analysis (weighted distance matrix) for predicting ship costs are $R = 0.93$ (coefficient of correlation as calculated by Equation 1) and $R^2 = 0.86$. The latter coefficient of determination indicates that 86% of the total variation in the ship costs can be explained by an average cost of the known ships weighted by an optimized distance metric. The mean absolute percent error is 16% and the standard deviation is 55.9 million NCC—improvements over the hierarchical clustering based on the simple distance metric.

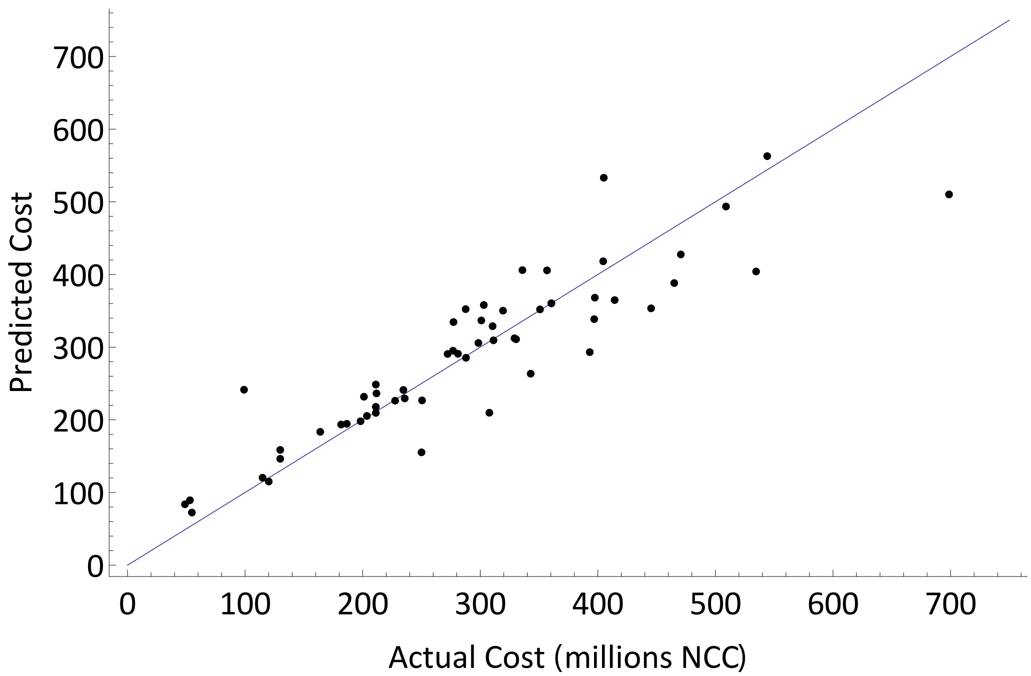

Figure 9: Weighted hierarchical clustering: correlation plot of actual vs. predicted ship costs (millions of NCC).

4.3 Discussion

Figure 9 shows that the analogy method using hierarchical clustering based on a weighted distance metric underestimates the cost of seven of the eight most expensive ships (all over 406 million NCC). This was also a characteristic of the parametric estimation presented in Section 3.2. In the latter it was conjectured that the underestimation was likely a result of the smoothing and pruning functions of the M5 model tree algorithm, designed to optimize the predictive capability of the method. However, the underestimation of expensive ships in the second, independent method, are potentially an indication that the attributes (and their values) of the SAS-076 ship data set do not provide enough information to help distinguish the highest costing ships from their peers.

5.0 RESULTS

The results of the M5 model tree system are described in Subsection 5.1. The point estimates obtained using the simple linear regression (Equation 4) and multiple linear regression (Equation 5) CER models are revealed in Subsection 5.2. Subsection 5.3 details the results of the hierarchical clustering method, Subsection 5.4 discusses which result should be considered the primary estimate, and in Subsection 5.5 the results of both models are are compared with the actual production and development costs (revealed post estimation).

5.1 M5 Model Tree Results

The technical specifications of HMS Rotterdam LPD (Table 3) were used to trace down the M5 model tree depicted in Figure 4. In particular, the input data indicates that HMS Rotterdam LPD does not have the capacity to carry LCAC in its well deck, carries one torpedo decoy system, and is ranked first in class. This results in linear regression model LM3 as per Table 4. Similarly, the attributes of HMS Johan de Witt LPD are used to follow the same path in the M5 model tree to linear regression model LM3. The linear regression model LM3 has the ship's rank in class, length, range in terms of sailing time in hours and distance (nm), number of LCAC, and number of torpedo decoy systems as independent variables. Using the LM3 model, the predicted development and production cost of HMS Rotterdam LPD is 197.7 million NCC. The predicted cost of HMS Johan de Witt LPD is 212.3 million NCC[15].

Figures 10 and 11 illustrate the log-normal probability density and cumulative distribution functions for the M5 model tree estimates for the cost of HMS Rotterdam LPD and HMS Johan de Witt LPD.

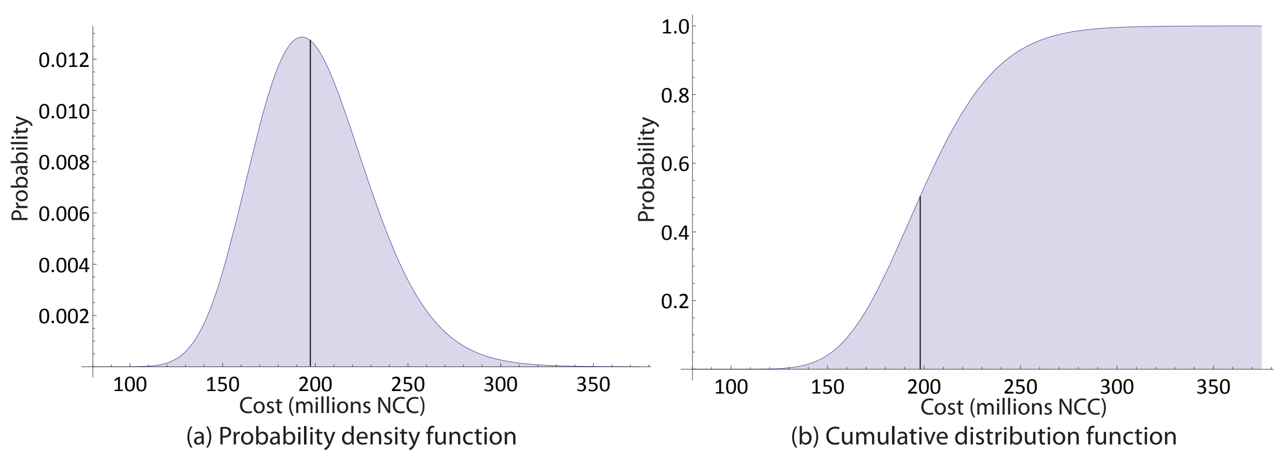

Figure 10: Probability density function (a) and cumulative distribution function (b) of the M5 model tree estimate of HMS Rotterdam LPD cost.

Table 10 lists the predicted costs for incremental percentiles of the fitted log-normal probability density functions. The predicted costs coincide to the 50th percentile of the respective log-normal probability distribution functions. This effect is explained by Goldberger [24]: when a power-function form is used for a CER, attention shifts from the mean to the median as a measure of central tendency; the CER yields an estimate of the

[15] HMS Rotterdam LPD and HMS Johan de Witt LPD differ in range (distance and sailing time in hours) and length—two of the independent variables in LM3.

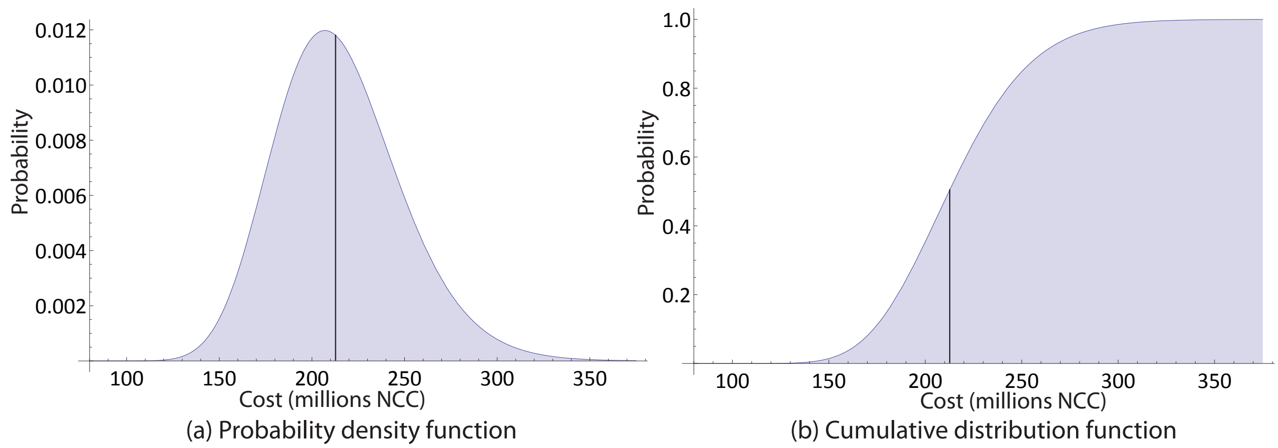

Figure 11: Probability density function (a) and cumulative distribution function (b) of the M5 model tree estimate of HMS Johan de Witt LPD cost.

median value of Y rather than the mean. The mean of the presented log-normal distributions are 200.2 million NCC and 215.0 million NCC for HMS Rotterdam LPD and HMS Johan de Witt LPD respectively.

Table 10: Percentiles of the fitted log-normal density functions for the M5 model tree estimated HMS Rotterdam LPD and HMS Johan de Witt LPD costs (millions NCC).

Percentile	HMS Rotterdam	HMS Johan de Witt
0.05	152.2	163.5
0.10	161.3	173.2
0.15	167.7	180.1
0.20	173.0	185.7
0.25	177.6	190.7
0.30	181.9	195.3
0.35	186.0	199.7
0.40	189.9	203.9
0.45	193.8	208.1
0.50	197.7	212.3
0.55	201.7	216.6
0.60	205.8	221.0
0.65	210.2	225.7
0.70	214.9	230.7
0.75	220.1	236.3
0.80	226.0	242.7
0.85	233.1	250.3
0.90	242.3	260.2
0.95	256.7	275.7

5.2 Linear Regression Results

Using simple linear regression CER, Equation 4, the estimate for HMS Rotterdam LPD is 219.2 million NCC. The estimate for HMS Johan de Witt LPD is 289.7 million NCC. Using the multiple linear regression CER, Equation 5, the estimate for HMS Rotterdam LPD is 158.9 million NCC. The estimate for HMS Johan de Witt LPD is 201.4 million NCC.

5.3 Hierarchical Cluster Analysis Results

The technical specifications of HMS Rotterdam LPD (Table 3) were mapped to the ten attributes selected by the principal component analysis (see Annex **??**). Using the optimized macro-attribute weights determined in Section 4.2, the normalized relative distances of HMS Rotterdam LPD to the other ships are listed in Table 11 (the distances have been normalized so that the furthest ship has a distance of 1). The resulting hierarchical clustering cost estimate for HMS Rotterdam LPD is 214.6 million NCC, and 243.9 million NCC for HMS Johan de Witt LPD.

Figures 12 and 13 illustrate the log-normal probability density and cumulative distribution functions for the hierarchical cluster estimates for the cost of HMS Rotterdam LPD and HMS Johan de Witt LPD. Table 12 lists the predicted costs for incremental percentiles of the fitted log-normal probability density functions. The mean of the presented log-normal distributions are 219.8 million NCC and 249.8 million NCC for HMS Rotterdam

Table 11: Weighted distance of the Rotterdam LPD to ships in the Rotterdam data set.

Name	Distance	Name	Distance	Name	Distance
Rotterdam	0.000	Vancouver	0.312	Nashville	0.639
Largs Bay	0.034	La Salle	0.316	Trenton	0.646
Lyme Bay	0.034	Harpers Ferry	0.405	Ponce	0.650
Mounts Bay	0.035	Carter Hall	0.431	Whidbey Island	0.655
Cardigan Bay	0.035	Oak Hill	0.435	Germantown	0.659
Oden	0.039	Pearl Harbour	0.439	Fort McHenry	0.664
Carlskrona	0.044	Anchorage	0.546	Gunston Hall	0.668
Johan de Witt	0.046	Portland	0.550	Comstock	0.673
Atle	0.052	Pensacola	0.553	Tortuga	0.678
Albion	0.057	Mount Vernon	0.557	Rushmore	0.682
Bulwark	0.058	Fort Fisher	0.561	Ashland	0.687
Siroco	0.067	Austin	0.601	Thomaston	0.971
Svalbard	0.068	Ogden	0.606	Plymouth Rock	0.975
Protecteur	0.128	Duluth	0.610	Fort Snelling	0.979
Preserver	0.129	Cleveland	0.612	Point Defiance	0.983
Ocean	0.227	Dubuque	0.617	Spiegel Grove	0.987
Tonnerre	0.244	Denver	0.621	Alamo	0.992
Mistral	0.246	Juneau	0.626	Hermitage	0.996
BPC3	0.266	Coronado	0.630	Monticello	1.000
Raleigh	0.309	Shreveport	0.634		

LPD and HMS Johan de Witt LPD respectively.

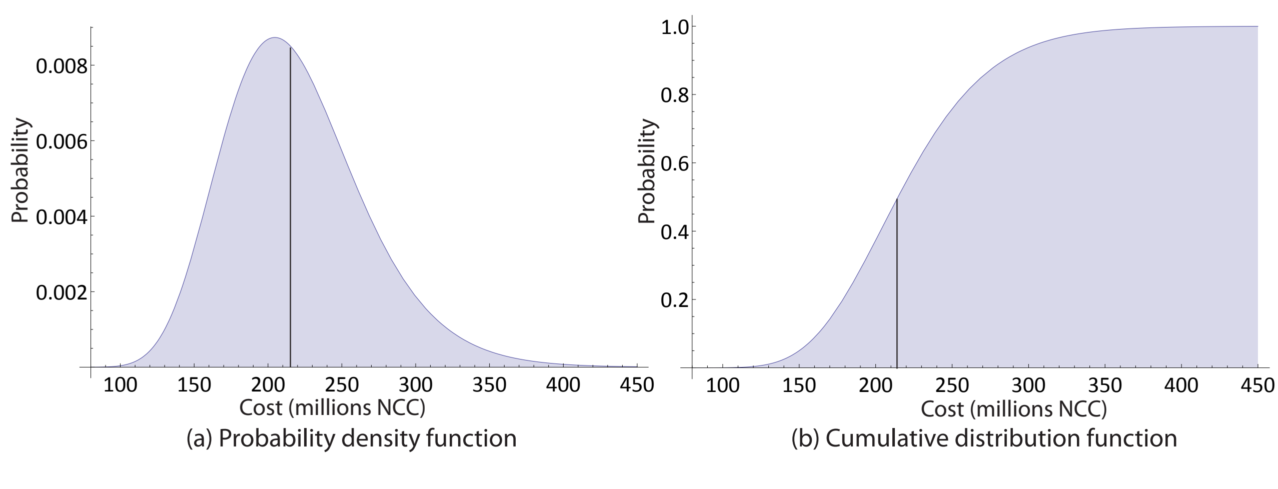

Figure 12: Probability density function (a) and cumulative distribution function (b) of the hierarchical clustering estimate of HMS Rotterdam LPD cost.

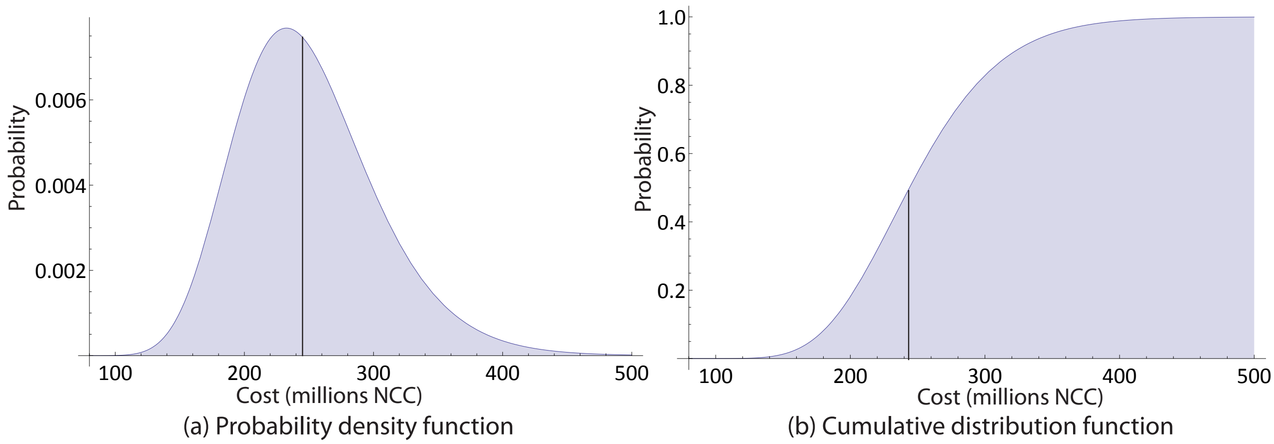

Figure 13: Probability density function (a) and cumulative distribution function (b) of the hierarchical clustering estimate of HMS Johan de Witt LPD cost.

Table 12: Percentiles of the fitted log-normal density functions for the hierarchical clustering estimated HMS Rotterdam LPD and HMS Johan de Witt LPD costs (millions NCC).

Percentile	HMS Rotterdam	HMS Johan de Witt
0.05	143.1	170.4
0.10	153.7	184.5
0.15	161.3	194.6
0.20	167.6	203.0
0.25	173.2	210.6
0.30	178.4	217.6
0.35	183.3	224.3
0.40	188.1	230.8
0.45	192.9	237.3
0.50	197.7	243.9
0.55	202.6	250.7
0.60	207.8	257.7
0.65	213.2	265.3
0.70	219.1	273.4
0.75	225.7	282.5
0.80	233.2	293.0
0.85	242.3	305.7
0.90	254.3	322.5
0.95	273.1	349.1

5.4 Discussion

The estimates generated by the M5 model tree are considered to be the primary estimates for HMS Rotterdam and Johan de Witt, the hierarchical clustering estimates are considered as secondary estimates. This decision was driven by the following:

- The M5 model tree algorithms are optimized to both learn known cases and predict unknown cases. The attribute weights used in the hierarchical clustering method are optimized to learn the known cases.
- The hierarchical clustering approach uses principal component analysis to reduce the dimensionality of the attribute space. Due to computational limitations, the weight optimization method could only be applied on the top ten macro-attributes, accounting for 80% of the original data set's variability. In comparison, the M5 model tree algorithm is computationally superior as it efficiently learns from large data sets.
- The M5 model tree results in a better correlation measure, lower mean absolute percent error, and smaller standard deviation in estimating the known cases.

Table 13 synthesizes the predictions and compares properties of the M5 model tree and hierarchical clustering methods.

Table 13: Comparison of the M5 model tree and hierarchical clustering methods and their estimates.

	M5 model tree	Hierarchical clustering
HMS Rotterdam estimate	197.7M NCC	214.6M NCC
HMS Johan de Witt estimate	212.3M NCC	243.9M NCC
Coefficient of correlation	0.96	0.93
Coefficient of determination	0.92	0.86
Standard deviation	46.4M NCC	55.9M NCC
Mean absolute % error	11%	16%
Ability to learn known cases	✓	✓
Optimized to predict unknown cases	✓	×
Uses entire data set	✓	×

In Subsections 5.1 and 5.3, the cost estimates outputted by the M5 system and the hierarchical clustering method were fitted to log-normal distributions. The probability distributions of the cost and the associated percentile breakdowns provide decision makers the ability to choose a budget based on a risk tolerance. The risk-averse decision maker will choose a higher budget amount to minimize the budget risk—the probability that the actual cost of a weapon system acquisition program will end up exceeding a given budget.

5.5 Ex Post Revelation

The Royal Netherlands Navy revealed the actual development and production costs of HMS Rotterdam and Johan de Witt LPDs to the NATO RTO SAS 076 Task Group once the cost estimates were established. The costs were then normalized to the fictitious notional common currency. Figures 14 and 15 illustrate where the actual costs (thick vertical lines) fall with respect to the log-normal probability density and cumulative distribution functions for the M5 model tree and hierarchical cluster cost estimates for HMS Rotterdam LPD and Johan de Witt LPD. Respecting the wishes of the Netherlands, even the exact fictitious costs are not made more explicit.

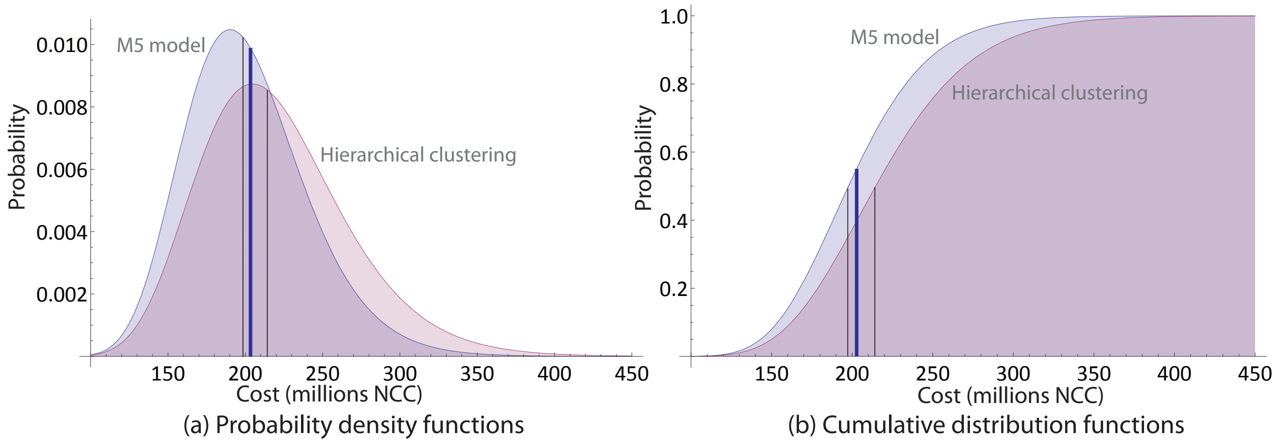

Figure 14: Probability density function (a) and cumulative distribution function (b) of the M5 model tree (blue) and hierarchical clustering (red) estimates of HMS Rotterdam LPD cost.

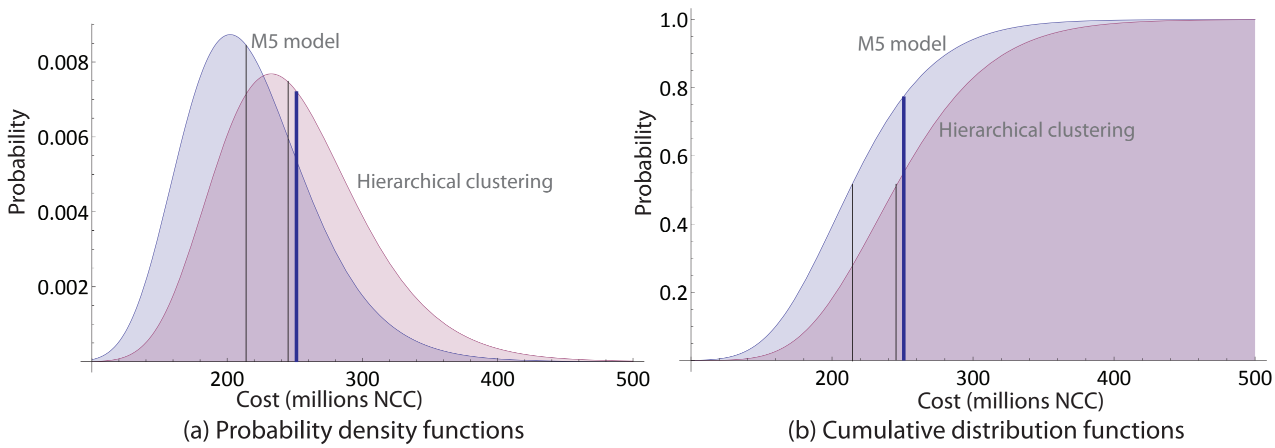

Figure 15: Probability density function (a) and cumulative distribution function (b) of the M5 model tree (blue) and hierarchical clustering (red) estimates of HMS Johan de Witt LPD cost.

Table 14 compares the actual development and production costs of HMS Rotterdam and HMS Johan de Witt to the estimates generated by the M5 model tree and hierarchical clustering methods. The percent error of the M5 model tree estimates (50th percentile) relative to the actual costs are -2% (under estimated) for HMS Rotterdam LPD and -16% (under estimated) for HMS Johan de Witt LPD. The percent error of the hierarchical clustering estimates (50th percentile) relative to the actual costs are 6% (over estimated) for HMS Rotterdam LPD and -4% (under estimated) for HMS Johan de Witt LPD. With respect to the fitted log-normal distributions,

Table 14: Comparison of actual to estimated costs (millions NCC).

	M5 model tree estimate	% error	Hierarchical clustering estimate	% error
HMS Rotterdam	197.7	-2%	214.6	6%
HMS Johan de Witt	212.3	-16%	243.9	-4%

the actual costs lie at the 55th (HMS Rotterdam LPD) and 80th (HMS Johan de Witt LPD) percentiles for the M5 model tree results, and at the 39th (HMS Rotterdam LPD) and 57th (HMS Johan de Witt LPD) percentiles for the hierarchical clustering results.

In retrospect, it is interesting to recall the discussion of Section 3.2 on the negative coefficient of a ship's sailing range in the M5 model tree's linear regression models. It was noted that the majority of the ships had a range under 770 hours, the impact on the estimated cost of these ships would be minimal while lowering estimates of ships with outlying sailing ranges (over 1200 hours). HMS Johan de Witt LPD's sailing range is listed as 833 hours. Substituting the median sailing range (444 hours) of the SAS-076 data set, effectively neutralizing the attribute, would result in a revised estimate of 253.9 million NCC, which is within 1% of the actual cost. The M5 model tree estimate of HMS Rotterdam LPD less sensitive to this factor as its sailing range is 500 hours, already quite close to the median of 444 hours, neutralizing the attribute by substituting the median sailing range results in a revised estimate of 202.8 million.

6.0 LESSONS IDENTIFIED

This section intends to capture the feedback and lessons identified on estimating acquisitions costs of the Netherlands' Landing Platform Dock Ships Rotterdam and Johan de Witt. The section is divided in six parts: general management of the estimating process; aims and cost boundary; data and assumptions; methods, models and tools; risk and uncertainty; and analysis and presentation of results.

6.1 General Management of the Estimating Process

Initial Plan

SAS-076 started with a plan describing the activities and captured this in a Project Initiation Document (PID). Originally it was described as follows:

> *For the acquisition stage a top-down approach will be adopted, using the information in the DADD and applying the parametric method. As a second estimating method it is possible to apply the analogy method using public available data (Internet, NAO (UK) report, etc).*

Initially the cost-estimating approach consisted of two iterations. The first iteration was to estimate high-level cost elements of the cost breakdown structure. This would result in many assumptions; these assumptions would need to be checked by the Royal Netherlands (RNL) Navy. It would have been used to identify cost drivers. The second iteration was to go into more details for the costs drivers, if additional data was available. The main milestones for the first iteration were:

- Milestone 1: Agreement on cost elements to be calculated - 16/01/2009.

- Milestone 2: Release of the data and assumptions list - 26/06/2009.
- Milestone 3: Release of first report - 22/01/2010.

The main Milestones for the second iteration were:

- Milestone 4: Agreement on new cost elements to be calculated - 22/01/2010.
- Milestone 5: Release of the updated data and assumptions list - 09/07/2010.
- Milestone 6: Release of second iteration report - 01/10/2010.

Actual Implementation of the Initial Plan

The following steps were actually followed after having established the PID:

- Agreement on the Cost Breakdown Structure (CBS): follow ANEP 41 (SWBS) and the CBS from SAS-054 report;
- Developed a Data and Assumptions Document Definition (DADD) based on the data found in public sources, participants' inputs and the RNLN;
- Investigated software tools to be used; and,
- Decision on methods to be used: analogy and parametric.

Canadian participants proposed to use a data mining parametric method based on model regression trees and a new analogy method based on clustering analysis. The proposal stemmed from SAS-054 Section 4.4 recommendation that *"The best cost estimating method is one that makes the best use of the data available. It is therefore recommended to employ a method that will provide as much detail as the availability of the input data will allow. Therefore, the availability of data is a major factor in the estimator's choice of estimating method."* The team decided to follow the Canadian proposal and to deviate from the original plan. By adopting this approach the second iteration was considered not applicable any more. In addition, the SAS-076 started to write the report when the first decisions were made and when the cost estimation models were developed. During the estimating process SAS-076 decided not to further develop the DADD as a separate document. Data used and the assumptions made are included in the final report.

Lessons Identified

The group did not work continuously on this project, causing additional challenges in the estimates and in the management of some important issues. The SAS-076 group considered the estimating guidelines and the tasks described in SAS-054 of the management process to be useful. The group tried to follow the SAS 054 guidelines the work as much as possible, however the group was restricted by the limited available resources and competence available in the group or available within the group members professional network. This affected, in a certain extent, the work process. The conclusion is that following the SAS 054 guidelines could be followed, however it takes some time and resources. Therefore the resources and the budget required to do an estimate according to the SAS-054 guideline should be carefully planned before the actual work starts.

6.2 Definition of the Aims and Cost Boundary

Team's approach

The customer for the results of the study is the Royal Netherlands Navy. As this estimate is also used to apply the guideline developed by SAS-054, NATO RTO can be considered as a (secondary) customer. The aim was to practice the guidelines. For the acquisition cost estimation the objective was to compare the results from the SAS-076 analysis with the actual acquisition costs.

Lessons Identified

The aim and the objective of the study are fundamental for the way the cost analysis is conducted.

6.3 Data and Assumptions

Team's Approach

SAS-076 gathered data from ships similar to the Netherlands LPD's. The group applied some subjectivity in selecting the ships for gathering data, but the group did not limit themselves to ships very close to the Netherlands' LPDs. Civilian ships like icebreakers were also included because data related to these ships may have information relevant for the Netherlands' LPDs. The group assumed accuracy in the data. Engineers or shipbuilders were used sparingly in validating the data. Rather, participants were asked to validate their national data. SAS-076 had to deal with some limitations:

- No distinction was possible between development and production costs. Not all data elements could be found; however the methodologies proposed for acquisition handled missing values.
- Not all cost data available was subdivided into work breakdown structure items.

Technical data related to the ships has mainly been gathered from open source. Sources used were Jane's Fighting Warships, Federation of American Scientists, Navy Matters, Forecast international, Wikipedia, etc. Regarding cost normalization, the difficulty stands in the different currencies (CAD, EURO, GBP, USD, NOK, SEK) and the different base years (1952 - 2010) for the data collected. The costs were normalized to a common currency and then to a common base year (and subsequently adjusted to a notional common currency for sensitivity reasons). The methodology consists of using an index to take into account inflation, then converting to the common currency with the exchange rate in the chosen base year. Often no publicly available total ship costs index per nation exist, let alone a multinational one. SAS-076 considered a multitude of indices and approaches, for example:

- The application the U.S. Bureau of Labor Statistics index for shipbuidling labour;
- The application of Eurostat labour indices;
- The ratio of a country's Ground Domestic Product (GDP) (between original cost data year and a common year) to obtain the Then Year local currency cost and then use the market exchange rate to get cost in the common currency — abandoned because it was deemed too astray from the shipbuilding industry; and,
- Consumer Price Index taken from International Monetary Fund (IMF) International Financial Statistics (IFS) Yearbooks and IMF/World Economic Outlook database—abandoned because too far from shipbuilding industry.

The final approach decided upon is presented in Section 2.2.

Lessons Identified

- It took quite some time to gather all data required to estimate the costs for the acquisition stage. Data collection was a tedious process spanning many iterations over many months. Internet searches of publicly available databases were used to select the NATO ships that are similar in nature to the Netherlands' LPDs. Janes Fighting Warships and Federation of American Scientists were used to compose a database template of attributes. This template was sent around to SAS-076 participants to fill or validate. Cost data was obtained from national sources contacted by respective SAS-076 participants.

- The group decided it was not necessary to use a MDAL, CARD, DADD or equivalent to capture data and assumptions in a stringent way. The group used a spreadsheet containing all the parameters needed without a identification of sources for each data gathered. This simplified approach was found to be sufficient if no official endorsement is needed for data and assumptions collected.

- An important lesson is that the cost normalization procedure is very important. The choice of a certain index will have a major impact on the results. SAS-054 report is not very explicit in the approach to follow for cost normalization. A more detailed description of how to deal with cost normalization would be helpful.

6.4 Methods, Models and Tools

Team's approach

As recommended in the SAS-054 Report, two independent methods were used for estimating acquisition costs. For the acquisition costs the analogy method and the parametric method were used. For these methods two data mining techniques were applied, which is a new method for cost analysis and considered to be very useful:

- Parametric method: a model tree that is a combination of decision trees and linear regression from which a Cost Estimating Relationships (CERs) is obtained;

- Analogy method: cluster analysis that consists first of identifying the nearest neighbours to both Rotterdam and Johan de Witt ships by first defining a distance function between ships and use the distances and known costs to obtain cost estimates for the Rotterdam and Johan de Witt.

The tools investigated were mainly commercial. It was not possible to acquire one of the tools, due to the very limited resources available. Therefore the group used tools that are publicly available (e.g., the WEKA-tool).

Lesson Identified:

- The data available determined, in a very large extent, the choice of methods. Finding input data has been the criteria to make the process go forward. It was a continuous interaction between choices of methods and computer models and availability of data. For acquisition costs the group assumed that many detailed data would be publicly available; and the group assumed that for sufficient ships, cost data would be available. This allowed the data mining method to be used. The data mining method did not constrain the selection of attributes. Generally, commercial tools fix the range of attributes.

- The new methodology used, based on data mining, is very valuable as it requires only publicly available technical data of attributes and some cost data. However, this method is not mentioned in the SAS-054 report. On the other hand the complexity of the analogy method based on hierarchical clustering lead to computational difficulties when using over one hundred attributes. This issue was dealt with by applying principal component analysis and reducing the dimensionality of the input without significant loss of information.

6.5 Risk and Uncertainty Analysis

Team's Approach

SAS-076 considered the risk and uncertainty analysis task implicitly: the two cost estimating methods produce probability distributions modeling the statistical uncertainty in the prediction—this is the uncertainty of the models. SAS-076 did not consider a full range of uncertainty on the input attributes or on the indices used, however sensitivity analysis was performed. Another issue related to the uncertainty of the acquisition costs concerns the missing data. However, the methodologies used to estimate the acquisition costs were able to handle missing values. Other relevant issues related to the uncertainty of the acquisition costs regard whether the attributes collected by SAS-076 describe the ships completely. It is not clear how the uncertainty could be considered in this case (e.g., if the costs of the more expensive ships are underestimated, is it possible that an important attribute is not accounted for?). These issues are not explicitly covered by the group.

Lessons Identified

- Uncertainty analysis of the acquisition cost estimation consisted of documenting and presenting the predictive capabilities of the data mining methods used: their accuracy on historical systems and the uncertainty in the predicted cost of the Rotterdam and Johan de Witt ships. Probability distributions and cumulative distribution functions were developed and presented graphically and in tabular format to allow a decision maker to select the desired confidence level (and associated cost) of the estimates.

- Further uncertainty analysis could have helped, but was not undertaken. This could have consisted of a Monte Carlo simulation to model different inflation and exchange rates, and could substitute missing attribute values (in lieu of just the mean) - each Monte Carlo iteration would feed the revised data into the data mining algorithms to output the associated cost estimate. This effort was deemed to require substantial programming effort to automate - the value gained was not clear.

- Using cost data from different sources may be a risk. In this study it was not certain if all cost data gathered from different sources have used the same cost boundary. E.g., personnel costs are not always considered in the same way. This issue was covered by assuming that all sources use the same cost boundary.

- Risk analysis, interpreted as examining the chance of loss of injury due to an unfavorable event, was not considered.

6.6 Analysis and Presentation of Results

Team's Approach

SAS-076 did not define a strategy for analysis as such but undertook the following ad hoc analyses for acquisition costs:

- One data outlier was removed from the analysis. This was the San Antonio LPD-17 whose cost overruns are well documented. The LPD-17 cost was more than three orders of magnitude larger than the minimum ship costs.
- The analysis of the initial cluster analysis results, where attributes were given equal weighting, showed poor predictive capability (low correlation of determination, R^2). The group then decided to determine the set of attribute weights that optimized prediction of known instances. This was a non-linear convex optimization problem too large to solve in a reasonable amount of time and memory. To circumvent computation issues subjectively chosen attribute subsets (less than 15 at a time) were tested. Each of these provided a better R^2. To eliminate the subjectivity, a subsequent iteration used principal component analysis to reduce the dimensionality of the data set while accounting for a large percentage of the original data's variability.
- The reason for selecting the M5 model estimate to be the primary estimate was due to the model construction: M5 Model trees are built to optimize prediction of unseen cases; the hierarchical clustering approach is optimized on learning the known cases.
- From this choice, a closer look at the CER showed that rank in class is one of the cost-driving attributes. However, SAS-076 had a doubt regarding Johann de Witt's rank in class. Through discussions with RNLN and the analysis of technical data, SAS-076 concluded that Johann de Witt is considered a separate class. In retrospect, this decision lead to a more accurate estimate.
- SAS-076 tried to determine ANEP-41 ESWBS cost category estimates. Given that only 10 data points (all from U.S.) were available, the effectiveness of data mining techniques was limited. It was suggested to take average percentages. However, results triggered the team that ESWBS items were not interpreted in the same way. Also for not many ships this detailed data was available and forced the team to skip the method to estimate costs at the ESWBS item level.
- The results of the acquisition costs estimate were presented to the RNLN, using the probability distribution with uncertainties. It was felt that the presentation fitted the customer's expectations.

Lessons Identified

- A critical approach on the first results obtained is highly recommended. The group demonstrated that without this critical look, the results obtained would have been less satisfactory for the acquisition costs.

7.0 CONCLUSION

This report describes two novel approaches to cost estimation using known data mining algorithms. As a proof of concept, the approaches were applied in a blind ex post cost estimation exercise of the Netherlands' landing platform dock ships.

Both methods incorporate a multitude of cost driving factors that required the compilation of a multinational data set of dozens of somewhat similar ships. The data mining approaches allow for a greater variability in the input data set—variability that could be questioned when using traditional approaches. As with other parametric and analogy approaches, the fidelity of the estimation models are very dependent the data set, especially if the size of the data set is small. Both are "top down" approaches applicable in early design phases of the procurement cycle.

The parametric approach combined features of decision trees with linear regression models to both classify similar ships (based on attributes) and build piece-wise multivariate linear regression models. The attributes of HMS Rotterdam class ships were use to trace down the tree and as input to the resulting regression models which outputted a prediction.

As an analogy costing approach, hierarchical agglomerative cluster analysis, principal component analysis, and non-linear optimization was used to calculate a matrix of distances among the data set ships. These distances were then used to predict the cost of HMS Rotterdam class ships.

Despite a limited data set, the proof of concept results provide evidence that the methods can provide accurate estimates. The methods should be considered for generating cost estimates for other systems for which ample data is available.

The methods herein used for cost estimating are new in the cost environment. Newly developed methods in other areas than cost analysis should always be considered for application in the cost analysis area. The cost analysis societies should be aware of new developments in methods and techniques in other related areas in order to apply them to cost analysis. This is in-line with SAS-054 recommendation O.9.7 stating "Research should be conducted continuously to enhance methods and models for life cycle costing." The methods proved to be valuable as they require only publicly available technical data of attributes and some cost data. In general, no major amendments or changes to the SAS-054 guideline are required, however some enhancements are suggested:

- Differentiate between approaches and methods: parametric, analogy, and engineering methods can each be applied in a top-down or bottom-up approach.
- The SAS-054 guidelines for cost normalization should be expanded to consider multi-national data sets where different currencies and base years are present. The approach taken by SAS-076 in this study can be used as an example.

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Appendix B1-1: DATA SET

Table 15: Technical data for the United Kingdom, Swedish, Norwegian, and French ships.

Data Category & Element	Albion	Largs Bay	Ocean	Carlskrona	Atle	Oden	Svalbard	Siroco	Mistral
I. DESCRIPTION									
e. Rank in class	1	1	1	1	1	1	1	2	1
f. Vessel type	Mil	Mil	Mil	Mil	Civ	Civ	Civ	Mil	Mil
II. CONSTRUCTION									
h. Civilian classification stnds.?	N	?	Y	Y	?	Y	Y	N	Y
III. DIMENSIONS									
a. Length (m)	176	176.6	203.4	105.7	104.6	107.8	103.7	168	199
b. Beam (m)	28.9	26.4	34.4	15.2	23.8	31	19.1	23.5	32
c. Draught (m)	7.1	5.8	6.6	4	8.3	8.5	6.5	5.2	6.2
d. Displacement Light	14600	13690	?	3150	?	11000	?	8230	16529
e. Displacement Full Load	18500	16160	21758	3800	9500	13000	6300	12400	21600
IV. PERFORMANCE									
a. Top speed	18	18	19	20	19	16	17	21	19
i. Range: Total distance	8000	8000	8000	?	?	30000	10000	11000	11000
ii. Range: Econ. speed	15	15	15	?	?	13	13	15	15
iii. Range: Sailing time	533	533	533	?	?	2308	769	733	733
b. Endurance (days)	?	?	?	?	56	100	?	30	45
c. Crew: complement	325	60	491	170	20	15	48	218	177
i. Officers	?	?	?	?	?	?	?	18	20
ii. Non-officers	?	?	?	?	?	?	?	200	157
V. PROPULSION									
a. Propulsion technology	Electric	Electric	Diesel	Diesel	Electric	Diesel	Electric	Diesel	Electric
b. Propeller shafts	2	0	2	2	4	2	0	2	0
i. Shaft power (MW)	?	0	13.5	7.76	16.2	18	0	15.3	0
ii. Propeller type	LIPS	N/A	fp	cp	?	cp	N/A	LIPS cp	N/A
c. Propulsion pods	0	2	0	0	?	0	2	0	2

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Data Category & Element	Albion	Largs Bay	Ocean	Carlskrona	Atle	Oden	Svalbard	Siroco	Mistral
i. Total power (MW)	0	4.4	0	0	?	0	10	0	14
d. Net power (MW)	?	?	13.5	7.76	?	18	10	15.3	14
e. Bow Thrusters	1	1	1	?	?	0	1	1	1
i. Total power (MW)	0.865	?	0.45	?	?	0	?	0.735	1.5
VI. ELECT. POWER GEN.									
a. Generators	4	4	?	?	?	4	4	5	4
i. Total capacity (MW)	15.6	11.2	?	?	16.2	?	13.56	4.25	20.8
ii. Generator technology	Diesel	Diesel	Diesel	?	Diesel	Diesel	Diesel	Diesel	Diesel
VII. LIFT CAPACITY									
a. Vehicle fuel (litres)	?	?	?	?	?	?	?	?	?
b. Aviation fuel (litres)	?	?	?	?	?	?	?	?	1071.3
c. Fresh water (litres)	?	?	?	?	?	310000	?	?	380
d. Bulk cargo space (m^3)	?	?	?	?	?	?	?	?	?
e. Vehicle space (m^2)	?	2875	?	0	0	0	0	?	2650
f. Well deck (Y/N)	Y	Y	N	N	N	N	N	Y	Y
i. Length (m)	?	95.5	0	0	0	0	0	122	?
ii. Width (m)	?	14	0	0	0	0	0	14.2	?
iii. Capacity (m^2)	?	1440	0	0	0	0	0	1732.4	885
iv. LCAC	2	0	0	0	0	0	0	?	2
v. LCM 6	?	?	0	0	0	0	0	?	?
vi. LCM 8	?	?	0	0	0	0	0	?	?
vii. LCU	4	2	0	0	0	0	0	?	4
viii. LVT	?	?	0	0	0	0	0	?	?
ix. LCVP	?	2	0	0	0	0	0	?	?
x. LCPL	?	?	0	0	0	0	0	?	?
xi. EFV	?	?	0	0	0	0	0	?	?
g. Cargo/Aircraft Elevator/Lifts	?	?	2	0	?	?	0	1	3
i. Capacity $\leq$ 5 tonnes	?	?	?	0	?	?	0	0	?
ii. 5 < capacity $\leq$ 10 tonnes	?	?	?	0	?	?	0	0	?
iii. 10 < capacity $\leq$ 15 tonnes	?	?	?	0	?	?	0	0	?

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Data Category & Element	Albion	Largs Bay	Ocean	Carlskrona	Atle	Oden	Svalbard	Siroco	Mistral
iv. Capacity $\geq$ 15 tonnes	?	?	?	0	?	?	0	1	?
h. Cranes	?	2	?	?	?	3	0	1	?
i. Capacity $\leq$ 5 tonnes	?	0	?	?	?	1	0	0	?
ii. 5 < capacity $\leq$ 10 tonnes	?	0	?	?	?	1	0	0	?
iii. 10 < capacity $\leq$ 15 tonnes	?	0	?	?	?	1	0	0	?
iv. 15 < capacity $\leq$ 20 tonnes	?	0	?	?	?	0	0	0	?
v. 20 < capacity $\leq$ 25 tonnes	?	0	?	?	?	0	0	0	?
vi. 25 < capacity $\leq$ 30 tonnes	?	2	?	?	?	0	0	0	?
vii. 30 < capacity $\leq$ 40 tonnes	?	0	?	?	?	0	0	1	?
viii. 40 < capacity $\leq$ 50 tonnes	?	0	?	?	?	0	0	0	?
ix. 50 < capacity $\leq$ 60 tonnes	?	0	?	?	?	0	0	0	?
x. Capacity > 60 tonnes	?	0	?	?	?	0	0	0	?
i. Berthing (troop capacity): Baseline	305	356	480	?	?	65	?	470	450
j. Berthing (troop capacity): Surge	305	344	323	?	?	?	?	?	450
VIII. FLIGHT DECK									
a. Equipped with flight deck? (Y/N)	Y	Y	Y	Y	?	?	Y	Y	Y
b. Flight deck length (m)	64	?	170	?	?	?	?	?	199
c. Flight deck width (m)	?	?	31.7	?	?	?	?	?	32
d. Flight deck area (m^2)	?	?	5389	?	?	?	?	1740	6368
e. Helicopter landing spots (max. #)	2	2	6	?	?	?	1	3	6
i. Merlin / Sea King	2	2	6	?	?	?	?	?	?
ii. NH 90 / Lynx / Puma / Cougar	?	?	?	?	?	?	?	3	6
iii. CH-46E Sea Knight	?	?	?	?	?	?	?	?	?
iv. CH-53 Sea Stallion	?	?	?	?	?	?	?	?	1
v. MV-22 Osprey	?	?	?	?	?	?	?	?	1
f. Chinook capable (Yes/No)	Y	Y	Y	N	?	?	N	?	Y
g. Equipped with hangar? (Y/N)	N	N	Y	N	?	?	N	?	Y
h. Hangar size (m^2)	0	0	2338	0	?	?	0	?	1800
i. Helicopters supported (max. #)	2	?	18	0	?	?	1	4	16
i. Merlin / Sea King	?	?	12	0	?	?	?	?	?

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Data Category & Element	Albion	Largs Bay	Ocean	Carlskrona	Atle	Oden	Svalbard	Siroco	Mistral
ii. NH 90 / Lynx / Puma / Cougar	?	?	6	0	?	?	1	4	16
iii. CH-46E Sea Knight	?	?	?	0	?	?	?	?	?
iv. CH-53 Sea Stallion	?	?	?	0	?	?	?	?	?
v. MV-22 Osprey	?	?	?	0	?	?	?	?	?
IX. ARMAMENT									
a. Guns (calibre $\geq$ 75mm)	0	0	0	0	0	0	0	0	0
b. Guns (50mm $\leq$ calibre < 75mm)	0	0	0	2	0	0	1	0	0
c. Guns (30mm $\leq$ calibre < 50mm)	0	0	0	2	0	0	0	3	2
d. Guns (20mm $\leq$ calibre < 30mm)	2	0	8	0	0	0	0	0	0
e. 30mm CIWS (Goalkeeper)	2	0	0	0	0	0	0	0	0
f. 20mm CIWS (Phalanx)	0	0	3	0	0	0	0	0	0
g. Machine guns (12.7mm)	0	0	0	0	0	0	?	4	4
h. Machine guns (7.62mm)	4	6	4	0	0	0	?	0	0
i. SSM launchers	0	0	0	0	0	0	0	0	0
j. SAM launchers	0	0	0	0	0	0	0	3	2
k. # of torpedos carried	0	0	0	0	0	0	0	0	0
l. Torpedo tubes	0	0	0	0	0	0	0	0	0
m. Torpedo launchers	0	0	0	0	0	0	0	0	0
X. COUNTERMEASURES									
a. Chaff launchers	8	?	8	2	0	0	0	0	0
b. Torpedo decoys	1	?	1	0	0	0	0	1	1
c. Other systems	0	?	0	0	0	0	0	0	0
d. Number of ESM systems	1	?	1	1	0	0	0	0	1
e. Number of ECM systems	1	?	1	0	0	0	0	2	0
XI. RADARS/TACAN/IFF/SONARS									
a. Total radar systems mounted	3	1	4	5	?	?	2	4	3
i. A-band	0	0	0	0	?	?	0	0	0
ii. B-band	0	0	0	0	?	?	0	0	0
iii. C-band	0	0	0	0	?	?	0	0	0
iv. D-band	0	0	0	0	?	?	0	1	0

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Data Category & Element	Albion	Largs Bay	Ocean	Carlskrona	Atle	Oden	Svalbard	Siroco	Mistral
v. E-band	2	0	2	1	?	?	0	0	0
vi. F-band	2	0	2	1	?	?	0	0	0
vii. G-band	0	0	0	1	?	?	1	0	1
viii. H-band	0	0	0	1	?	?	0	0	0
ix. I-band	1	1	2	4	?	?	1	3	2
x. J-band	0	0	0	2	?	?	0	0	0
b. # of TACAN/IFF systems mounted	1	?	1	?	?	?	?	?	?
c. # of distinct sonar systems mounted	0	?	0	?	?	?	0	?	0
XII. COMBAT DATA SYSTEMS									
a. Number of distinct systems	5	?	6	?	?	?	?	5	7
XIII. WEAPONS CONTROL SYSTEMS									
a. Number of distinct systems	2	?	?	?	?	?	?	2	2
XIV. OTHER CAPABILITIES									
a. Equipped with hospital? (Y/N)	?	?	?	Y	?	Y	N	Y	Y
i. Number of beds	?	?	?	?	?	?	0	47	69
ii. Operating rooms	?	?	?	?	?	?	0	2	2
iii. X-Ray facility (Y/N)	?	?	?	?	?	?	N	?	Y
b. Dental capability (Y/N)	?	?	?	?	?	?	N	?	?
c. Command/Control facility (Y/N)	Y	?	Y	?	?	?	N	?	Y
d. NBCD Facilities (Y/N)	?	Y	Y	?	?	?	Y	?	?

Table 16: Technical data for the United States and Canadian ships.

Data Category & Element	Thomaston	Anchorage	Whidbey Island	Harpers Ferry	Raleigh	Austin	San Antonio	Protecteur
I. DESCRIPTION								
e. Rank in class	1	1	1	1	1	1	1	1
f. Vessel type	Mil	Mil	Mil	Mil	Mil	Mil	Mil	Mil
II. CONSTRUCTION								
h. Civilian classification stnds.?	N	N	N	N	N	N	N	N
III. DIMENSIONS								
a. Length (m)	160	168.6	185.8	185.8	159.1056	173.8	208.4	171.9
b. Beam (m)	26	25.6	25.6	25.6	30.48	30.5	31.9	23.2
c. Draught (m)	5.8	6	6.3	6.3	7.0104	7	7	10.46
d. Displacement Light	9042	8600	11125	11125	8789	9130	18477	9259
e. Displacement Full Load	11710	13700	15939	16740	14339	17244	25885	25676
IV. PERFORMANCE								
a. Top speed	21	22	22	22	21	21	22	21
i. Range: Total distance	13000	14800	8000	8000	9600	7700	?	7500
ii. Range: Econ. speed	10	12	18	18	16	20	?	11.5
iii. Range: Sailing time	?	1233	444	444	600	385	?	652
b. Endurance (days)	?	?	?	?	?	60	?	?
c. Crew: complement	341	374	413	352	429	420	396	335
i. Officers	29	24	21	24	29	24	32	38
ii. Non-officers	312	350	392	328	400	396	364	297
V. PROPULSION								
a. Propulsion technology	Steam	Steam	Diesel	Diesel	Steam	Steam	Diesel	Steam
b. Propeller shafts	2	2	2	2	2	2	2	1
i. Shaft power (MW)	17	17.9	24.6	24.6	17.9	17.9	29.84	15.7
ii. Propeller type	?	?	cp	cp	?	?	cp	?
c. Propulsion pods	0	0	0	0	0	0	0	0
i. Total power (MW)	0	0	0	0	0	0	0	0
d. Net power (MW)	17	17.9	24.6	24.6	17.9	17.9	29.84	15.7
e. Bow Thrusters	0	0	0	0	0	0	0	1

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Data Category & Element	Thomaston	Anchorage	Whidbey Island	Harpers Ferry	Raleigh	Austin	San Antonio	Protecteur
i. Total power (MW)	0	0	0	0	0	0	0	?
VI. ELECT. POWER GEN.								
a. Generators	?	?	4	4	?	4	5	?
i. Total capacity (MW)	?	?	5.2	5.2	?	?	12.5	?
ii. Generator technology	Steam	Steam	Diesel	Diesel	?	Steam	Diesel	?
VII. LIFT CAPACITY								
a. Vehicle fuel (litres)	?	?	?	?	?	?	37850	?
b. Aviation fuel (litres)	?	110200	110000	110000	?	?	1173500	?
c. Fresh water (litres)	?	?	?	?	?	?	?	?
d. Bulk cargo space (m^3)	99	?	141.6	1914	?	?	963	?
e. Vehicle space (m^2)	?	?	1161	1877	?	?	2285	?
f. Well deck (Y/N)	Y	Y	Y	Y	Y	Y	Y	N
i. Length (m)	120.7	131.1	134.1	?	51.2	120.1	?	0
ii. Width (m)	15.24	15.2	15.2	15.2	15.2	15.2	?	0
iii. Capacity (m^2)	1840	1992.72	2038.32	?	778.24	1825.52	?	0
iv. LCAC	?	3	4	2	2	2	2	0
v. LCM 6	21	18	21	9	3	9	?	0
vi. LCM 8	9	9	10	4	4	4	?	0
vii. LCU	3	3	3	1	1	?	1	0
viii. LVT	48	50	64	64	20	20	?	0
ix. LCVP	?	?	?	?	?	4	?	4
x. LCPL	?	?	2	2	?	4	?	0
xi. EFV	?	?	?	?	?	?	14	0
g. Cargo/Aircraft Elevator/Lifts	?	?	0	0	?	1	3	0
i. Capacity $\leq$ 5 tonnes	?	?	0	0	?	0	1	0
ii. 5 < capacity $\leq$ 10 tonnes	?	?	0	0	?	1	2	0
iii. 10 < capacity $\leq$ 15 tonnes	?	?	0	0	?	0	0	0
iv. Capacity $\geq$ 15 tonnes	?	?	0	0	?	0	0	0
h. Cranes	3	2	3	1	?	7	2	2
i. Capacity $\leq$ 5 tonnes	0	0	0	0	?	6	2	0

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Data Category & Element	Thomaston	Anchorage	Whidbey Island	Harpers Ferry	Raleigh	Austin	San Antonio	Protecteur
ii. 5 < capacity ≤ 10 tonnes	1	0	0	0	?	0	0	0
iii. 10 < capacity ≤ 15 tonnes	0	0	1	0	?	0	0	2
iv. 15 < capacity ≤ 20 tonnes	0	0	1	0	?	0	0	0
v. 20 < capacity ≤ 25 tonnes	0	0	0	0	?	0	0	0
vi. 25 < capacity ≤ 30 tonnes	0	0	0	1	?	1	0	0
vii. 30 < capacity ≤ 40 tonnes	0	0	0	0	?	0	0	0
viii. 40 < capacity ≤ 50 tonnes	2	2	0	0	?	0	0	0
ix. 50 < capacity ≤ 60 tonnes	0	0	1	0	?	0	0	0
x. Capacity > 60 tonnes	0	0	0	0	?	0	0	0
i. Berthing (troop capacity): Baseline	325	366	402	402	930	900	699	0
j. Berthing (troop capacity): Surge	?	?	102	102	?	?	101	0
VIII. FLIGHT DECK								
a. Equipped with flight deck? (Y/N)	Y	Y	Y	Y	Y	Y	Y	Y
b. Flight deck length (m)	?	?	64.6	?	?	51.2	?	?
c. Flight deck width (m)	?	?	25.3	?	?	?	?	?
d. Flight deck area (m^2)	?	?	1634.38	?	?	?	?	?
e. Helicopter landing spots (max. #)	1	1	2	2	?	2	4	?
i. Merlin / Sea King	?	?	?	?	?	?	?	?
ii. NH 90 / Lynx / Puma / Cougar	?	?	?	?	?	?	?	?
iii. CH-46E Sea Knight	?	?	?	?	?	2	4	?
iv. CH-53 Sea Stallion	?	1	2	2	?	2	2	?
v. MV-22 Osprey	?	?	?	?	?	0	2	0
f. Chinook capable (Yes/No)	?	?	?	?	?	?	?	N
g. Equipped with hangar? (Y/N)	?	N	N	N	N	N	Y	Y
h. Hangar size (m^2)	?	0	0	0	0	0	?	?
i. Helicopters supported (max. #)	8	1	2	0	6	6	2	3
i. Merlin / Sea King	?	?	0	0	?	?	?	3
ii. NH 90 / Lynx / Puma / Cougar	?	?	0	0	?	?	?	0
iii. CH-46E Sea Knight	?	?	0	0	6	6	2	0
iv. CH-53 Sea Stallion	?	1	2	0	?	3	1	0

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Data Category & Element	Thomaston	Anchorage	Whidbey Island	Harpers Ferry	Raleigh	Austin	San Antonio	Protecteur
v. MV-22 Osprey	?	?	0	0	?	?	1	0
IX. ARMAMENT								
a. Guns (calibre $\geq$ 75mm)	4	4	0	0	8	4	0	1
b. Guns (50mm $\leq$ calibre < 75mm)	0	0	0	0	0	0	0	0
c. Guns (30mm $\leq$ calibre < 50mm)	0	0	0	0	0	0	2	0
d. Guns (20mm $\leq$ calibre < 30mm)	6	0	2	2	0	0	0	0
e. 30mm CIWS (Goalkeeper)	0	0	0	0	0	0	0	0
f. 20mm CIWS (Phalanx)	0	0	2	2	0	0	0	0
g. Machine guns (12.7mm)	?	6	6	6	0	8	4	6
h. Machine guns (7.62mm)	?	0	0	0	0	0	0	0
i. SSM launchers	?	0	0	0	0	0	0	?
j. SAM launchers	?	0	2	2	0	0	2	?
k. # of torpedos carried	?	0	0	0	0	0	0	0
l. Torpedo tubes	?	0	0	0	0	0	0	0
m. Torpedo launchers	?	0	0	0	0	0	0	0
X. COUNTERMEASURES								
a. Chaff launchers	?	0	4	6	0	0	6	6
b. Torpedo decoys	?	0	1	1	0	0	1	0
c. Other systems	?	0	0	0	0	0	0	0
d. Number of ESM systems	?	1	2	2	1	1	1	1
e. Number of ECM systems	?	0	0	0	0	0	1	0
XI. RADARS/TACAN/IFF/SONARS								
a. Total radar systems mounted	?	3	3	3	3	3	3	3
i. A-band	?	0	0	0	0	0	0	0
ii. B-band	?	0	0	0	0	1	0	0
iii. C-band	?	0	1	1	0	0	0	0
iv. D-band	?	0	0	0	0	0	0	0
v. E-band	?	1	0	0	1	0	1	0
vi. F-band	?	1	0	0	1	0	1	0
vii. G-band	?	1	1	1	1	1	0	1

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Data Category & Element	Thomaston	Anchorage	Whidbey Island	Harpers Ferry	Raleigh	Austin	San Antonio	Protecteur
viii. H-band	?	0	0	0	0	0	0	0
ix. I-band	?	1	1	1	1	1	2	2
x. J-band	?	0	1	1	0	0	0	0
b. # of TACAN/IFF systems mounted	?	?	1	1	1	1	?	1
c. # of distinct sonar systems mounted	?	0	0	0	0	0	0	0
XII. COMBAT DATA SYSTEMS								
a. Number of distinct systems	?	2	3	3	2	3	5	2
XIII. WEAPONS CONTROL SYSTEMS								
a. Number of distinct systems	?	?	?	?	?	?	?	?
XIV. OTHER CAPABILITIES								
a. Equipped with hospital? (Y/N)	N	?	Y	Y	?	Y	Y	Y
i. Number of beds	0	?	?	?	?	12	24	8
ii. Operating rooms	0	?	?	?	?	?	2	1
iii. X-Ray facility (Y/N)	N	?	?	?	?	Y	?	Y
b. Dental capability (Y/N)	N	?	Y	Y	?	Y	Y	Y
c. Command/Control facility (Y/N)	N	?	?	?	?	Y	?	?
d. NBCD Facilities (Y/N)	?	?	?	?	?	?	?	Y

Appendix B1-2: PRINCIPAL COMPONENT DATA SET

Table 17: Principal component analysis (80% coverage): resulting attributes.

Name	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Rotterdam	-0.6206	2.4141	0.7228	-0.9292	-0.4955	0.7275	2.2589	1.8520	-0.3011	1.2791
Johan de Witt	-1.2649	2.8019	0.5701	-0.5635	-0.8626	0.4325	2.3956	1.3758	0.0415	1.4135
Thomaston	1.9276	3.1298	-0.1413	1.5096	0.7688	-0.1155	0.4850	1.1027	-0.3971	0.5587
Plymouth Rock	1.9379	3.1359	-0.1478	1.5097	0.7631	-0.1156	0.4846	1.1057	-0.3994	0.5546
Fort Snelling	1.9482	3.1419	-0.1543	1.5099	0.7574	-0.1156	0.4841	1.1087	-0.4017	0.5505
Point Defiance	1.9585	3.1480	-0.1608	1.5101	0.7517	-0.1157	0.4836	1.1117	-0.4040	0.5463
Spiegel Grove	1.9687	3.1541	-0.1673	1.5103	0.7460	-0.1158	0.4831	1.1147	-0.4063	0.5422
Alamo	1.9790	3.1602	-0.1738	1.5104	0.7403	-0.1159	0.4826	1.1176	-0.4086	0.5381
Hermitage	1.9893	3.1662	-0.1803	1.5106	0.7346	-0.1160	0.4821	1.1206	-0.4109	0.5340
Monticello	1.9995	3.1723	-0.1868	1.5108	0.7290	-0.1161	0.4816	1.1236	-0.4132	0.5298
Anchorage	1.7511	3.4262	0.0422	0.1333	0.1469	0.1039	0.4367	1.1533	0.5488	1.2309
Portland	1.7614	3.4323	0.0357	0.1335	0.1412	0.1038	0.4362	1.1562	0.5465	1.2268
Pensacola	1.7716	3.4384	0.0292	0.1337	0.1355	0.1038	0.4357	1.1592	0.5442	1.2227
Mount Vernon	1.7819	3.4444	0.0227	0.1339	0.1298	0.1037	0.4352	1.1622	0.5419	1.2185
Fort Fisher	1.7922	3.4505	0.0162	0.1340	0.1241	0.1036	0.4347	1.1652	0.5396	1.2144
Whidbey Island	2.2519	3.5869	2.5713	-0.4678	-0.9544	-0.4128	0.0767	1.0708	-0.3635	1.0883
Germantown	2.2622	3.5930	2.5648	-0.4676	-0.9600	-0.4129	0.0763	1.0738	-0.3658	1.0842
Fort McHenry	2.2724	3.5991	2.5583	-0.4674	-0.9657	-0.4130	0.0758	1.0768	-0.3681	1.0801
Gunston Hall	2.2827	3.6052	2.5518	-0.4673	-0.9714	-0.4131	0.0753	1.0798	-0.3704	1.0759
Comstock	2.2930	3.6112	2.5453	-0.4671	-0.9771	-0.4132	0.0748	1.0828	-0.3727	1.0718
Tortuga	2.3032	3.6173	2.5388	-0.4669	-0.9828	-0.4133	0.0743	1.0858	-0.3750	1.0677
Rushmore	2.3135	3.6234	2.5323	-0.4667	-0.9885	-0.4134	0.0738	1.0887	-0.3773	1.0635
Ashland	2.3238	3.6294	2.5258	-0.4666	-0.9942	-0.4134	0.0733	1.0917	-0.3796	1.0594
Harpers Ferry	1.6647	3.2549	2.1292	-0.8805	-0.5622	-0.2858	0.1686	0.7128	-0.4586	0.9417
Carter Hall	1.7338	3.3117	2.1975	-0.7664	-0.5860	-0.2634	0.2029	0.7011	-0.4489	0.9213
Oak Hill	1.7440	3.3178	2.1910	-0.7663	-0.5917	-0.2635	0.2024	0.7041	-0.4512	0.9172
Pearl Harbour	1.7543	3.3239	2.1845	-0.7661	-0.5973	-0.2636	0.2019	0.7071	-0.4535	0.9131
Raleigh	1.3761	3.3173	-0.3228	-1.0441	0.0914	0.1091	0.0184	0.8934	-0.3140	1.3569
Vancouver	1.3864	3.3233	-0.3293	-1.0439	0.0857	0.1090	0.0179	0.8964	-0.3163	1.3528
La Salle	1.3967	3.3294	-0.3358	-1.0437	0.0800	0.1089	0.0174	0.8994	-0.3186	1.3487
Austin	2.1235	4.0747	-1.0059	-1.4247	-0.6041	0.2968	0.0522	1.0929	-0.2233	0.9882
Ogden	2.1338	4.0808	-1.0124	-1.4245	-0.6098	0.2967	0.0518	1.0959	-0.2256	0.9841
Duluth	2.1441	4.0868	-1.0189	-1.4243	-0.6155	0.2966	0.0513	1.0988	-0.2279	0.9800
Cleveland	2.1509	4.0852	-1.0177	-1.4156	-0.6195	0.2900	0.0523	1.0992	-0.2269	0.9703
Dubuque	2.1612	4.0913	-1.0242	-1.4154	-0.6252	0.2899	0.0518	1.1022	-0.2292	0.9662
Denver	2.1714	4.0973	-1.0307	-1.4153	-0.6308	0.2899	0.0514	1.1052	-0.2315	0.9621
Juneau	2.1817	4.1034	-1.0372	-1.4151	-0.6365	0.2898	0.0509	1.1082	-0.2338	0.9579
Coronado	2.1920	4.1095	-1.0437	-1.4149	-0.6422	0.2897	0.0504	1.1112	-0.2361	0.9538
Shreveport	2.2022	4.1155	-1.0502	-1.4147	-0.6479	0.2896	0.0499	1.1141	-0.2384	0.9497
Nashville	2.2125	4.1216	-1.0567	-1.4146	-0.6536	0.2895	0.0494	1.1171	-0.2407	0.9456
Trenton	2.2262	4.1354	-1.0709	-1.4229	-0.6610	0.2959	0.0474	1.1227	-0.2464	0.9470
Ponce	2.2365	4.1415	-1.0774	-1.4227	-0.6667	0.2958	0.0469	1.1257	-0.2487	0.9428
Svalbard	-0.7433	1.1388	-0.4784	-0.0210	-0.1696	-0.7977	-0.3938	-0.2546	-0.0443	1.0611
Carlskrona	0.0059	0.9827	0.8272	-1.3437	0.1930	-0.0546	-1.1465	1.1058	-0.1787	2.0847
Atle	0.0467	1.9025	-0.0422	-1.3997	0.1531	-0.3840	-0.7034	0.2808	-0.2888	1.5649
Oden	0.0028	1.5587	0.0901	-1.2462	0.6961	-0.7923	-1.0531	0.4929	-0.0974	1.4152
Protecteur	0.4067	1.8877	0.6018	-1.6665	0.3229	-1.0168	-0.0801	1.1704	0.0202	0.5590
Preserver	0.4170	1.8938	0.5953	-1.6663	0.3172	-1.0168	-0.0806	1.1734	0.0179	0.5549
Albion	-0.0074	3.5859	0.8295	-0.4372	-0.1269	0.0663	1.7115	0.3668	-0.8352	2.2346
Bulwark	0.0029	3.5920	0.8230	-0.4370	-0.1326	0.0662	1.7110	0.3698	-0.8376	2.2304
Largs Bay	-0.3477	3.5454	0.2793	-0.3506	-1.0843	0.0178	0.7886	-1.0940	-0.5283	0.9502
Lyme Bay	-0.3375	3.5515	0.2728	-0.3504	-1.0900	0.0177	0.7881	-1.0910	-0.5306	0.9461
Mounts Bay	-0.3272	3.5575	0.2663	-0.3502	-1.0957	0.0177	0.7877	-1.0880	-0.5329	0.9420
Cardigan Bay	-0.3169	3.5636	0.2598	-0.3500	-1.1013	0.0176	0.7872	-1.0850	-0.5352	0.9378
Ocean	-1.3561	3.0070	0.8555	-1.2696	0.6200	-0.7988	0.0159	2.1329	-2.6844	1.2224
Siroco	-0.0044	3.5500	1.6121	-0.4833	-0.1249	2.0335	-0.2927	1.1556	0.5445	1.1961
Mistral	-2.0123	5.0343	0.5142	0.1228	-1.1827	-0.4498	-0.2610	1.3142	0.2379	0.5384
Tonnerre	-2.0020	5.0404	0.5077	0.1230	-1.1884	-0.4499	-0.2615	1.3172	0.2355	0.5343
Dixmude (BPC3)	-1.9670	5.0010	0.7382	0.2820	-1.4906	-0.5423	-0.3208	1.4085	0.2621	0.7027

Appendix B1-3: M5 MODEL TREE ALGORITHM

This Annex details the M5 model tree algorithm. It does not present original research and the algorithm itself should not be attributed to the authors of this paper. The reader is referred to Witten and Frank [14] and Wang and Witten [15] for further details.

The description of the algorithm is divided into four subsections: building the decision tree, fitting linear regression models, pruning the tree, and finally smoothing the tree. The two final subsections of this annex detail how the M5 system handles nominal attributes and missing data.

Building the Initial Decision Tree

The M5 model tree algorithm constructs a decision tree by recursively splitting the instance space (training set—e.g., the SAS-076 ship data set). Let T be the set of training data that reaches a particular node. A splitting criterion is used to determine which attribute, and what value of that attribute, is optimal to split T into sets T_L and T_R. The splitting criterion is based on minimizing the standard deviation of the known class values (e.g., ship cost) in T. The expected error reduction, or standard deviation reduction (SDR), is calculated by

$$SDR = sd(T) - \left(\frac{|T_L|}{|T|} \times sd(T_L) - \frac{|T_R|}{|T|} \times sd(T_R) \right), \tag{15}$$

where $sd(T)$ is the standard deviation of the class values in T.

The recursion stops at a particular node when the standard deviation is only a small fraction (e.g., 5%) of the standard deviation of the original instance set (at the root of the tree). Splitting also terminates when only a few instances remain $(T \leq 4)$[16].

Fitting Linear Regression Models

After the tree has been grown, the M5 system computes a linear regression model for every node N of the tree, recursively descending the tree. Each regression model has the form

$$w_0 + w_1 a_1 + w_2 a_2 + \ldots + w_k a_k, \tag{16}$$

where $a_1, a_2, \ldots, a_k$ are (numeric) attribute values. The weights $w_1, w_2, \ldots, w_k$ are calculated using standard multivariate linear regression. Only the attributes that are used for splitting decisions in the subtree below a node are used in the regression. The other attributes that affect the prediction value have been taken into account in the tests that lead to that node. Attributes are greedily dropped from a regression model if doing so improves the expected estimated error, computed as

$$Error(N) = \frac{n+v}{n-v} \times \frac{\sum_{instances} |\text{deviation from predicted class values}|}{n}, \tag{17}$$

where n is the number of instances at the node and v is the number of parameters in the node's regression model. This expected estimation error is calculated by averaging the absolute difference between the predicted value and the actual value for each of the training examples that reach that node. This results in underestimation of the expected error outside the calibrating data. As a compensation factor, the expected error is multiplied by $(n+v)/(n-v)$. Dropping a term decreases the latter multiplication factor, which may be enough to offset the increase in the average error over the training cases. This procedure is similar to the modification of the coefficient of determination, R^2, to the more representative $R^2_{adjusted}$ in regression theory [13].

[16]Experiments have shown that the results obtained are not very sensitive to the exact choice of these thresholds.

Pruning the Tree

Once the tree is built and linear regression models fitted for each node, the tree is recursively pruned from the leaves if this results in a lower expected estimated error. If T is the set of instances that reach a node, let the T_L and T_R be the split of these instances between the left (L) and right (R) children nodes. For each node N, the error calculated by equation (17) is compared to the expected error from the subtree below (branches L and R), recursively calculated as

$$subtreeError(N) = \frac{|T_L| \times subtreeError(L) + |T_R| \times subtreeError(R)}{|T|} \text{ if } N \text{ is an internal node,}$$
$$subtreeError(N) = Error(N) \text{ if } N \text{ is a leaf.} \tag{18}$$

Smoothing the M5 Model Tree

After pruning, the adjacent linear models will be sharply discontinuous at the leaves of the pruned tree. This problem is pronounced for models constructed from a small number of training instances. The M5 system applies a smoothing process combining the linear regression model at a leaf with the models on the path to the root to form the final model that is placed at the leaf. In effect, the estimated value of the leaf model is filtered along the path back to the root. At each node, that value is combined with the value predicted by the linear model for that node. The calculation is

$$p' = \frac{np + kq}{n + k}, \tag{19}$$

where p' is the prediction passed up to the next higher node, p is the prediction passed to this node from below, q is the value predicted by the model at this node, n is the number of training instances that reach the node below, and k is a constant. Experiments by Wang and Witten [15] showed that smoothing substantially increases the accuracy of predictions. After the smoothing process, the M5 model tree effectively has constructed piece-wise linear regression models.

Nominal Attributes

Nominal attributes are transformed into binary variables and then treated as numeric during the construction of the model tree. For each nominal attribute, the average class value (e.g., cost) corresponding to each possible attribute value is calculated from the training set. The attribute values are then sorted from smallest to largest average class value. A nominal attribute with k possible values is converted into $k-1$ synthetic binary variables: the i^{th} being 0 if the original nominal value is one of the first i in the sorted ordering and 1 otherwise.

Missing Values

To handle training instances with missing attribute values, the standard deviation reduction formula is modified to compensate for missing values. For an attribute for which $m > 1$ instances are missing, the formula, (15), re-written as

$$SDR = \frac{m}{|T|} \times \left[sd(T) - \left(\frac{|T_L|}{|T|} \times sd(T_L) - \frac{|T_R|}{|T|} \times sd(T_R) \right) \right]. \tag{20}$$

For instances with missing attribute values, a surrogate value is used during the construction of the model tree. The missing value is replaced with the average value of that attribute over the training instances that reach a particular node. Similarly, at the leaf level all missing values are replaced by the average values of the corresponding attributes of the training instances reaching the leaf.

Annex B2

Estimating the Operation and Support Costs of the Royal Netherlands Navy Landing Platform Dock Ships: an Ex Ante Analysis

NATO RTO Systems Analysis and Studies Task Group-076*

November 2, 2011

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1.0 INTRODUCTION

1.1 Background

SAS-076 set out to generate independent estimates of the Operation & Support (O&S) costs of the Netherland's Her Majesty Ship (HMS) Rotterdam Landing Platform Dock (LPD). This was an ex-ante analysis based on real organizational and operational data, followed-up with technical and economic data gathered from the Royal Netherlands Navy (RNLN). SAS-076 also generated an independent cost estimate (ICE) of the development and construction costs, labelled herein as acquisitions costs, for the LPD, which is described in Annex B1 of the SAS-076 report. The reader is referred to Annex B1 for technical data related to the HMS Rotterdam - the System of Interest (SoI) for this study.

For the selected systems, assumptions were made, technical data was gathered, and actual cost data was collected for the development, production and in-service phases. SAS-076 generated an independent cost estimate based on the SAS-054 guidelines [1] to estimate the O&S costs using 3 methods: *parametric, analogy* and *engineering "bottom-up"* methods. As expected, the latter was the most demanding in terms of resources and work-hours consumed.

The parametric and analogy method were used to develop an O&S cost estimate based on Cost Analysis Improvement Group (CAIG)[1] elements. This study was performed outside the SAS-076 by a group of researchers from the United States (U.S.) Naval Center for Cost Analysis (NCCA). The results of this study are attached to this report in Appendix 2. The engineering method estimates the O&S costs only for HMS Rotterdam, because logistic data was only available for this ship.

1.2 Objective

The objective of this report is to present the methods used, compare the results obtained, and describe the application of the engineering method for this study, as well as the benefits obtained and the difficulties encountered.

1.3 Scope

This report focuses mainly on the engineering method and how this should be used according to SAS-054 recommendations. As known, this method is not new in estimating costs, but remains a fundamental one.

1.4 Outline

Section 2 presents the methods used in this study; Section 3 presents the tools used to compute the O&S estimates; Section 4 defines the data and the assumptions; Section 5 describes the cost normalization; Section 6 presents the results of the analysis; Section 7 makes a comparison between the CAIG and the Generic Cost Breakdown Structure (GCBS) models; Section 8 provides the lessons learned;, and, Section 9 presents the conclusions. In the Appendices the CATLOC[2] model is described, the CAIG study is presented as well as the Cost Breakdown Structures used in both the CAIG and GCBS model.

[1] CAIG is now replaced by Cost Assessment and Program Evaluation (CAPE).

[2] Life cycle cost software from Systecon (http://www.systecon.co.uk/products/catloc/index.asp).

2.0 METHODOLOGY

The NATO RTO-TR-SAS-054 report recommended the use of more than one method. In this study, two independent O&S cost estimates were produced using 3 methods: *parametric, analogy* and *engineering "bottom-up"* methods.

2.1 Analogy Method

The analogy method compares a new system with one or more existing systems for which accurate cost and technical data are available. The historic system should be of similar size, complexity and scope.

2.2 Parametric Method

Parametric methods are based on various characteristics or measurable attributes of the system, hardware and software being estimated. It depends upon the existence of a causal relationship between system costs and these parameters. Such relationships, known as Cost Estimating Relationships (CERs), are typically estimated from historical data using statistical techniques. If such a relationship can be established, the CER will capture the relationship in mathematical terms, relating cost as the dependent variable to one or more independent variables.

2.3 Engineering "Bottom-up" Method

Engineering methods, as stipulated in the SAS-054 report, are the most detailed of all the techniques and the most costly to implement. This technique starts at the lowest level of definable work within the cost breakdown structure and builds up to a total cost. These types of estimates are used when detailed design data (Logistic Support Analysis Records) are available on the SoI.

Parametric and analogy methods were applied by experts from the U.S. Naval Centre for Cost Analysis and were based on U.S. ship data pulled from the U.S. Naval Visibility and Management of Operating and Support Costs (VAMOSC) management information system and averaged appropriately. These methods were applied on the U.S. Department of Defense (DoD) CAIG Cost Breakdown Structure (CBS). The cost obtained is the average annual O&S costs of a hull, not the specific O&S costs in a given year (see details in Appendix 2).

The Engineering bottom-up method was applied using data from the RNLN and was based on the CBS recommended in SAS-054, labelled herein as the GCBS. The results of applying this method can be found in Section 7. SAS-076 focused on the engineering method because it provided some key advantages:

- This type of method is a measure related to given requirements, and different requirements lead to different cost figures. It is also highlighting the critical aspects in the SoI design and its logistical organization, which also makes it a tool for project management and systems engineering.
- It provides a structured way of weighing significant technical and cost inputs.
- Even if the application of the method is expensive, its benefits may outweigh its cost[3].
- The application of the method shows the economical consequences of the technical system properties over time, which provides the means of evaluating the cost implication of a proposed system solution

[3] We should remember the saying credited to John Ruston: "It's unwise to pay too much, but it's foolish to spend too little" - this is the operating principle of the engineering method.

3.0 TOOLS

The tool used for the complete GCBS cost model was CATLOC. CATLOC is a tool that supports all the primary uses of Life Cycle Costing (LCC) presented in the NATO RTO-TR-SAS-054 report. Different uses of LCC typically require different LCC models, which can be implemented in CATLOC.

The most fundamental task in building an LCC model is to define the costs to be included in the model, and how to calculate them. LCC is broken-down in a cost breakdown structure, an LCC-tree, where it is expressed as the sum of sub costs or cost aggregates. These sub costs are recursively broken down, until at the lowest level the cost atoms are found. Cost atoms are costs that cannot be expressed as the sum of other costs; instead they are defined more explicitly in terms of parameters, constants and mathematical functions. Thus the only costs in CATLOC calculated through a formula are the cost atoms. The aggregated costs and the cost breakdown structure are used only to organize and group the cost atoms into logical groups. The purpose of grouping cost atoms into cost aggregates is to improve the possibilities for analyzing and understanding the calculated costs. For a given set of cost atoms there will exist many logical ways to group the cost atoms together. It will therefore be possible to create different cost breakdown structures, or cost views.

Based on the principles defined in NATO RTO-TR-058 (SAS-028) [2] and NATO RTO-TR-SAS-054 reports, a cost element (cost atom) shall be defined as follows: *a cost is due to the use of a Resource to perform an Activity for a Product over Time for a defined Customer*. This means that a cost atom shall be defined in five dimensions: Resource - Activity - Product - Time - Customer.

CATLOC allows the implementation of this principle. As a matter of fact, the tool offers functionalities that define cost atoms and parameters in five dimensions:

- MATERIAL (Product) e.g., systems and items in the material breakdown structure;
- TASK (Activity) e.g., corrective and preventive tasks performed on the technical system;
- RESOURCE e.g., resources required for operation and maintenance of the systems;
- STATION (Customer) e.g., stations where systems are operated and maintenance is performed; and,
- TIME e.g., the time periods of interest – "life's length".

The costs can be defined for a combination of the dimensions. A subset of the members in any dimension is called a domain. The five dimensions span a five dimensional space, and cost atoms and parameters are defined upon subsets of this five dimensional space. These subsets are called domains of definitions. The domain of definition for a cost atom or parameter is specified by giving a domain for the five dimensions. In each of the five dimensions, except the time dimension, it is possible to build a dimensional structure, i.e., define child objects and mother objects. The structure in the time dimension is implicitly defined by the order data is given in the time table.

The brief description above may not be easy to understand. For more details about the tool please refer to Systecon AB, Sweden, the developer and owner of this tool.

For the tools used in ex post testing parametric and analogy method see Appendix 2.

4.0 DATA AND ASSUMPTIONS

This chapter describes the data assumptions that were made in order to compute a cost estimate through an engineering approach. Most of the assumptions are based on information received from the RNLN, but in those instances where the data was not available an assumption was made to obtain a complete estimate.

Some of the parameters used in this Annex are described here. These are mainly the parameters connected to the general assumptions such as operational profile for the SoI and its maintenance organization. Parameters related to the reliability, maintainability and supportability of the system are also described here. These parameters were assumed to be found in an existing database. The rest of the parameters are presented in Appendix 1.

The abbreviations or designations used for all the parameters are at the discretion of the model designer. No standards exist. Because of the large number of abbreviations and their subjective character, an overview with all the acronyms used is not provided. The only references to the acronyms are found in this chapter, the following chapter, and Appendix 1.

4.1 Analogy and Parametric

For the analogy and parametric methods, the data captured represents initially 10 U.S. ships. Ultimately, 4 of them were dropped from the dataset because the dimensions of those classes were not analogous to the Rotterdam and Johan de Witt classes. One was dropped because there were only two years of data available for that class. Therefore, 5 ship classes were used in the final dataset.

Sources are the U.S. Naval VAMOSC management information system. VAMOSC collects and reports U.S. Navy and U.S. Marine Corps historical weapon system O&S costs. VAMOSC provides the direct O&S costs of weapon systems, some linked indirect costs (e.g., ship depot overhead), and related non-cost information such as flying hour metrics, steaming hours, age of aircraft, etc.

4.2 Engineering Bottom-up

For this assessment the O&S costs are estimated using both organizational and operational data as well as technical and economical data. Data was gathered by the RNLN and consists of the information described below. The level of confidence of the O&S cost is considered high when data was provided from national sources, and medium or low when provided from public available data.

However even data obtained from RNLN can be considered uncertain most of the time because the data that the group asked for was not provided and thus more calculations and/or approximations were done which inevitably induced more errors. Furthermore, the RNLN could not provide the group with all necessary data, mostly because of confidentiality reasons, which led to the use of publicly available data. In general, the results of the computation are considered to be of medium level of confidence. However, some cost atoms are considered to be of low level of confidence.

Each section below has a short description of the data and assumptions in qualitative and, whenever possible, in quantitative terms. Each section also includes a description of the parameters used in the cost model, and refers to a type of data or assumption. Some of the parameters and/or assumptions are only briefly described here. A more detailed explanation can be found in Appendix 1.

4.2.1 Organizational and Operational Data

Organizational and operational data and assumptions describe the operational profile, support organization of all stakeholders including the interfaces, and the administrative and logistic delay times according to national doctrines. It records also the requirements of the Nations in terms of measures of effectiveness. This section also describes data and assumptions related to the programme management organization, production organization, and test and trials organization.

4.2.1.1 Operational usage and types of missions

Operational usage defines the average operational time per system and year in hours. In the study it is assumed that the following operational profile is valid for the system's life cycle:

- War/crisis periods (when the system is assumed to be at sea) are defined in the model as **TOW** (average war/crisis operational time per system in hours per year).
- SAR missions (when the system is supposed to be at sea) are defined in the model as **TOS** (average SAR operational time per system in hours per year).
- Periods of time spent in foreign harbour, defined in the model as **TOH** (average operating time spent in harbour elsewhere in hours per year).
- Periods of time spent at home harbour, defined in the model as **TSB** (average operating time stand-by in hours per year).

These 4 types of operational time periods define the mission types and can be developed in more details if necessary. The first three periods above are considered as operational time and can be expressed as:

$$\mathrm{TO} = \mathrm{TOW} + \mathrm{TOS} + \mathrm{TOH}\,, \tag{1}$$

where **TO** is the average operational time per system per year, and is calculated as the sum of the other operational periods of time.

The model defines a period of time when the system is supposed to be at the contractor site for maintenance actions, **TSS** – average time stand-still in hours per year. This means that the sum of these periods of time and **TSB** (average operating time stand-by in hours per year) should be equal to the total number of hours per year, i.e.,

$$8760 = \mathrm{TO} + \mathrm{TSB} + \mathrm{TSS}\,. \tag{2}$$

All these periods of time have been deduced and computed from 10 years of Rotterdam class ship operational usage. In the model, which considers a 30 years life cycle for the system, an average value for the operational periods was computed for the missing data.

The input data from the RNLN was given for the time period between 2000 and 2009. The input parameters used are:

- **NSD** - the number of sailings days per year;
- **NDHH** - the number of days at home harbour, not including the time for major maintenance actions;
- **NDFH** - the number of days in foreign harbours or elsewhere (not at home harbour); and,
- **NHV** - the number of harbour visits elsewhere. The parameter NHV is not used in the model;

Using the input parameters, the periods of time defined above were calculated as follows:

$$\mathrm{TOW} = \mathrm{NSD} \times 24/2\,, \tag{3}$$

$$\mathrm{TOS} = \mathrm{NSD} \times 24/2\,, \tag{4}$$

$$\mathrm{TOH} = \mathrm{NDFH} \times 24\ , \tag{5}$$

$$\mathrm{TSB} = \mathrm{NDHH} \times 24\ , \tag{6}$$

$$\mathrm{TSS} = 8760 - \mathrm{TO} - \mathrm{TSB}\ . \tag{7}$$

The model defines with these periods of time two other parameters:

- **UTILF** - is a utilization factor describing the average fraction of operational time (TO) per calendar time.

$$\mathrm{UTILF} = \mathrm{TO}/8760\ . \tag{8}$$

- **UTILS** - is the utilization factor describing the average fraction operational time at sea per calendar time, calculated only over TOW and TOS

$$\mathrm{UTILS} = (\mathrm{TOW} + \mathrm{TOS})/8760\ . \tag{9}$$

The input values obtained from RNLN led to some uncertainties which still have not been resolved, i.e., it is unclear if NDFH includes only visits to foreign harbours or visits to the main contractor's docks. It is also unspecified if any major maintenance periods are included here. In the model, the assumption is that it does. This does not in any way affect the costs computation, at least not at the level of detail used in the model.

The operational profile is still very simple. In order to get all the benefits from the engineering method the definition of the operational profile and different types of missions should be described in much more detail.

4.2.1.2 Types of operators

According to the information received from RNLN, the manning profile is given in Table 1.
Assumptions used in Table 1 are:

Table 1: Rotterdam class ship manning profile

	Number of Accommodations	Number of Crew Members
Commander	1	1
Chief Officer	1	1
Officers	14	11
CPO's	28	22
Enlisted	84	78
Total	128	113

- The total number of 128 includes the reserves and equals the total number of accommodations on board the ship. The total of 113 is the actual number of crew members. It is considered that the number of persons included in the crew list, i.e., 113 will not change with the operational profile. The model considers the total number of persons including the reserves, i.e., 128.

- The costs related to the operating personnel on-board the ship is an average income per year, MIOP, i.e., 50.000 Euros,
- The model gives the possibility to implement more detailed costs related to the average yearly cost for personnel uniforms, accessories, shoes, special clothing, etc. through the parameter COPC, but the data was not available and this parameter is set to zero for the estimation.
- For the other types of personnel, the costs are captured at Maintenance Costs in association with either corrective maintenance actions or preventive maintenance actions.
- No increase in pay, inflation rate or present value factor is applied to the salaries.
- Because of the lack of data, other parameters such as operator tasks, i.e., categories of tasks necessary to operate the ship, or the quantity of personnel necessary to operate the ship, type of personnel and task, as well as the percentage of the working time dedicated to the operation of the ship per type of personnel and task category, were not included.
- According to RNLN there is a personnel cost associated to the helicopters operating from the ship. The data received from the RNLN is an average cost per year and is connected to the total personnel costs for the ship.

4.2.1.3 Consumables and all fluids

These assumptions reflect technical and economical data on fuel, oil and lubricants consumption, as well as other consumables, except repair parts. These consumables can be anything from office and personal computer supplies to water or other fluids, food and housekeeping materials.

4.2.1.3.1 Fuel

The input data from the RNLN contained the fuel consumption in litres per year for approximately 10 years. A conversion from cubic metres to metric ton was made. According to the Shell Oil Company, the density for maritime fuel-oil is between 840 – 990 $\mathrm{Kg/m^3}$, depending on the type of fuel. The average density chosen was 915 $\mathrm{Kg/m^3}$, leading to the following density coefficient used for conversion:

$$915/100 = 0.92\,. \tag{10}$$

This is an assumption, resting on the hope that some environmental considerations will be made when choosing the fuel.

The BWI (Bunkerworld Index) shows the actual price for different types of fuel in $/MT (metric ton). At the time of this study the prices varied between 600 and 960 $/MT. However, the average price in the last five years was between 370 and 670 $/MT, depending on the type of fuel. The average price used for the estimation is 370 euro/MT, using the present currency conversion from $ to euro, – parameter CLFS in the model.

Bunker Index (BIX) is the Average Global Bunker Price (AGBP) for all maritime gasoil port prices published on the Bunker Index website. More than 5 BIX were used to calculate the average price used in the model. The BIX is calculated by adding each individual daily fuel-type port assessment price and dividing by the number of prices. The statistics (the last five years prices) from the same source were used.

The fuel prices showed huge variations over the last few years; therefore the effect of this cost variation on the total LCC can be high, especially for yearly planning and budgeting. Due to the complexity of the estimation of future fuel prices, and due to the time and resources limitations the group faced, it has not been possible to calculate the costs using future fuel price estimates. However the user of the SoI can use estimations of the fluctuation of the fuel prices from professional sources and adjust the training days at sea according to the budget, or buy the necessary quantity of fuel when the prices are lowest for future years according to the planned operational profile. A storage cost will eventually arise. Of course, this can be done in peace time. In war time or crisis, the cost of fuel is still important, but the shortage of fuel is more important and the budget will need to be adjusted accordingly.

These are usually the reasons that, when using the engineering LCC method, lead to the elimination of these variations in the fuel prices. In using the engineering method, one goal is to find the cost drivers which then can be reduced or affected by the user of the system himself.

The average consumption (expressed in the model by MFCH) for the given 10 years is 3461 m^3 or 3,461,000 litres per year. Assuming that the cost for fuel is in average 370 euro/MT, then the average cost for fuel consumption is much higher than the average value given by the RNLN for yearly petroleum, oil, and lubricant (POL) consumption. The model assumes that the cost for the fuel consumption is not included in this value and an additional cost is calculated.

4.2.1.3.2 Oil and lubricants

In some publications, the oil consumption is said to be 100 times smaller than the fuel consumption at nominal power, i.e., about 1%. Other assumptions are that for large ships the oil consumption is larger than 10% of fuel consumption. In lack of actual follow-up data, it has not been possible to find reliable information to make anything but a rough estimation for the oil consumption.

In the model, a formula is used which calculates the oil consumption as 15% of the fuel consumption. The propulsion systems for Rotterdam, both primary and secondary systems, are diesel generators and motors. According to information gathered from specialized literature, diesel generators and motors have a rate of lubricants consumption that may approach 5% of the fuel consumption. This is the assumption used in the model.

4.2.1.3.3 Food and water

Reasonable water consumption level per person is about 150 litres/day. There are 128 people on the ship and they spend about 200 days on-board on average which gives a total water consumption of 3,840,000 litres or 3,840 m^3 per year. In The Netherlands, the water price is on average 2.6 euro/m^3. This results in about 10,000 euro/year only for personnel needs. We estimate that the minimum needs for water are at least 3 times higher.

No increase rate has been applied to the prices although there has been a larger increase in the price of water in the Netherlands than in many European countries. Organisation for Economic Co-operation and Development (OECD)[4] average real increase (%/year) was 4.6 between 1990 and 1998.

4.2.1.3.4 Other consumables

In the model, other consumables, such as the electricity consumption and other operational materials could be calculated. As no input data was obtained, those elements had no impact on the O&S costs.

[4] www.oecd.org

4.2.1.3 Munitions and countermeasures

Data supplied by the RNLN included an average cost per year for use of munitions and countermeasures for training and missions. No other assumptions are made.

4.2.1.4 Support concept and organization

For maintenance tasks, the following general maintenance levels are distinguished:

- Organizational Level Maintenance (OLM)
- Intermediate Level Maintenance (ILM)
- Depot Level Maintenance (DLM)
- Contractor Level Maintenance (CLM)

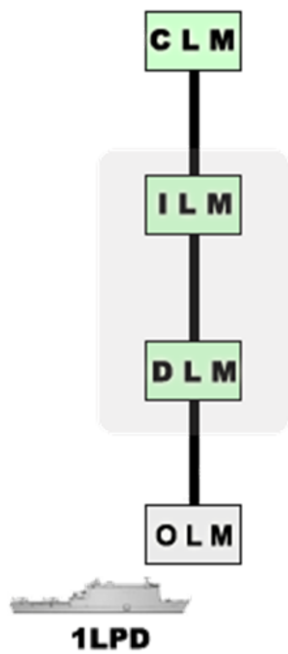

Figure 1: General maintenance levels

OLM - level

OLM-level consists of repairing failures by exchanging Line Replaceable Units (LRUs), preventive maintenance, corrective maintenance and condition monitoring. This is done by the crew of the ship, totally independent of any support from ashore. Basically the activities take place at sea or in the harbour. The maintenance personnel make use of tools, support equipment, spare parts and documentation on board the ship.

ILM/DLM - levels

Personnel employed at these levels are not specified in the model and subsequently no average income per year or month is specified either. The only cost taken into consideration here is the average man-hour cost, i.e., MHC, 65 euro/hr. However, the model gives the opportunity to specify the number of workers used for each preventive (PM) or corrective (CM) maintenance action on each part in the materiel structure, as well as the number of labour hours per each action.

Maintenance at ILM- and DLM-level is organised or done by the Marinebedrijf (Navy Maintenance Establishment, NME). The NME or third parties will do the complex and/or labour intensive maintenance tasks.

The crew of the ship can assist in the tasks at these levels (hours spent included in the maintenance capacity at OLM-level). Basically the NME will do their maintenance tasks during a scheduled maintenance period. Planned activities are done during the maintenance periods as captured in the yearly maintenance plan, as long as they are not part of a maintenance period during a mission. The NME will repair the failed or supposed to be failed mechanical and electronic LRUs, which then, after a check, will be added to the stock.

Statutory tasks, like yearly inspection and testing of pressurized containers and lifts, are always done by the NME. The same counts for calibration activities on Test and Support Equipment and tools.

For the activities at these levels, a larger set of tools or workshops ashore can be used. The electronic workshops will be equipped with the necessary tools, test equipment and test software, as far as it is considered.

The difference between these two levels is that activities at the ILM-level level are characterized by a short preparation time.

CLM - level

Contractor Level Maintenance is the maintenance that is done by industry. The contractor has specialized knowledge about the system and specialized equipment to perform the maintenance actions as efficiently as possible. Cost of contractor logistics support (CLS) captures the costs for using highly specialised personnel, and the costs of transportation related to these maintenance actions.

4.2.1.5 Logistic Support Elements

Data and assumptions for logistic support elements describe parts of the Integrated Logistic Support Elements (LSE) that are necessary for the costing study. These elements are: Documentation, Packaging, Handling, Storage & Transport, Facilities, Training and Training devices, data exchange and related information systems, and computer resource support.

4.2.1.5.1 Documentation update

No data was available from the RNLN if either investments in or updates of the documentation was needed to operate or to maintain the SoI.

The value of the investment costs for the documentation needed for a complex system like the Rotterdam LPD, can vary depending on how much experience the producer of such a system has, or how many systems are already produced. Assuming that the manufacturer of the system has such experience, but considering that only one system or very few have been produced and that The Rotterdam class might have been one of the first systems delivered to the customers, we can estimate the cost for initial documentation to around 8-10% of the total acquisition cost.

The yearly updates are on average 10 to 15% of the initial cost, but may be more depending on which technical modifications are carried out on the main system. Now included in this estimation is administration and transportation and any other costs connected with the documentation.

This is a very rough estimation, more so than should be accepted in a normal engineering estimation.

4.2.1.5.2 Continuous Training

By training, we mean the necessary courses to teach the personnel how to operate the system and how to maintain it. The type of parameters considered here are the training volume and types, as well as the cost per training type. Also considered is how many training devices are used and the cost for acquisition and maintenance of the devices. No data was made available from the RNLN

The assumption made here is that the yearly cost for training is comparable to the cost for documentation updates, or slightly lower. The value used is 10% lower than that for documentation updates. This simplified assumption excludes the initial cost for acquiring the necessary training devices or training documentation as well as the initial training events.

4.2.1.5.3 PHST (Packing, Handling, Storage, & Transporting)

Data obtained from the RNLN was:

- Materiel costs for handling of Government Owned Stores
- Man-Hour Costs for handling of Government Owned Stores

Initially, implemented in the cost model were parameters like: storage volume, percentage of storage areas used for the ship, storage costs or cost per m^3, as well as the frequency of transport per type of transport, and for each type of material to be transported: equipment spare parts, personnel, munitions and consumables. However, no data was available and these parameters were removed from the CBS.

N.B.: Other costs such as: costs for the support of the information systems (hardware/software); costs for embedded software and their support; costs for the use of the infrastructure at home or elsewhere (different types of fees) exist in the model. However, lack of data or other possibilities to estimate them have made their impact on the total outcome nil.

The assumptions made for training and documentation updates and for other similar assumptions are based on Swedish experience, and rely on data bases for similar costs for sea, air and land systems.

4.2.2 Technical Data

4.2.2.1 Life length of the system

Expected life length of the system is an input from the RNLN and is equal to 30 years. In CATLOC the built-in parameter, TIMEVAL, is taken into consideration in the TIME domain but is not explicitly used in any formulæ. More detailed information can be found in the description of the model.

4.2.2.2 System Breakdown Structure

This ICE used the generic CBS as defined in the SAS-054 Report. The cost elements that were estimated were defined iteratively. The list of the cost elements for this study as well as their definitions, are described in the next section. Furthermore the methodology defined in the SAS-028 Report with the generic resources, product and task dimensions were used; and for the definition of the generic System Breakdown Structure, ANEP-41 [3] was used. If necessary, these approaches were tailored according the specifics of the programme.

For the O&S costs (ex-ante estimate), even if not all the aggregates could be populated with input data, the costs were split into the generic System Breakdown Structure as follows:

- Group 000 General Guidance and Administration
- Group 100 Hull Structure
- Group 200 Propulsion Plant
- Group 300 Electric Plant
- Group 400 Command and Surveillance
- Group 500 Auxiliary System
- Group 600 Outfit and Furnishings
- Group 700 Armament
- Group 800 Integration/Engineering
- Group 900 Ship Assembly and Support Services

An example of the system breakdown structure and how this was used in the estimation is presented in Figure 2 as an Excel sheet, MtrlData, that includes the reliability data for each Item of the System Breakdown Structure. The structure can be adjusted by the system user.

Information from RNLN		System Materiel Data								
Basic Information							CM Replacements data			
MID	DESCR	SMID	TYPE	QTYPM	PRICE	FRT	LRE	MTTRP	NMTRP	CMRP
100	HULL STRUCTURE,	MAINSYS	ASSY	1	1	0	A	0	1	0
110	SHELL AND SUPPORTING STRUCTURE	100	SUBSYS	1	1	0	A	0	1	0
120	HULL STRUCTURAL BULKHEADS	100	SUBSYS	1	1	0	A	0	1	0
130	HULL DECKS	100	SUBSYS	1	1	0	A	0	1	0
140	HULL PLATFORMS AND FLATS	100	SUBSYS	1	1	0	A	0	1	0

Figure 2: Sample System Breakdown Structure

The values of the failure rates for the subsystems should be either the sum of the same parameter for the incorporated components of the subsystems or a "residual failure rate". To explain the term residual failure rate (RFRT), the following example is given: we assume that not all the components of a subsystem are listed in the input sheet, therefore the total failure rate for the subsystem can be greater than the sum of the failure rates for its listed components. So that the Total FRT (TFRTsubsys) for a subsystem equals the sum of the failure rates for its listed components plus the residual failure rate:

$$\text{TFRTsubsys} = \text{FRTlisteditem} + \text{RFRT}. \qquad (11)$$

If the values for the failure rates for a subsystem are zero, than the FRT listed will be used.

Figure 3 is a part of the Materiel Data sheet delivered to the RNLN to fill with follow-up data. The parameters seen in the columns are described below.

			CM Repairs data					
CMRPC	ACMRP	CMTRP	LCM	MTTR	NMTR	CMCM	ACMC	CMCMC
0	0	0	A	0	1	0	0	0
0	0	0	A	0	1	0	0	0
0	0	0	A	0	1	0	0	0
0	0	0	A	0	1	0	0	0
0	0	0	A	0	1	0	0	0

Figure 3: Input failure rates

4.2.2.3 Maintenance and support

4.2.2.3.1 Basic Input

The parameters in this section are the basic parameters connected to the reliability, maintainability and supportability (RAMS) data. Most of these parameters are well known from RAMS analysis

- IID — Item Identifier – the item ID tag is used as a unique identifier per item. An ID tag is defined in the input table. The value should be entered as a character string. There is no maximal length but a maximum around 10-12 characters is recommended. Delimiter characters can cause trouble when exporting data to text format.
- DESCR — is a free text column used to describe an item, system, materiel position, station, failure mode, preventive maintenance task or resource more in detail.
- MID — Mother item or System Identifier. It specifies the ID-tag of the mother unit in the material hierarchy. The mother unit is either a system or another item.
- TYPE — The type determines whether an item is repairable, partially repairable or discardable and whether it is a primary or secondary item. It can also specify that it is an assembly or subsystem. The default value is LRU or SRU depending on whether the item is primary or not.
  - LRU — Repairable primary item replaced directly in the system. An LRU can be a part of a subsystem, assembly or can be a part of the main system.
  - SRU — Repairable secondary item replaced in an LRU, SRU, PRU or SPRU at LEVEL2 and 3.
  - DU — Discardable primary item replaced directly in the system. A DU can be a part of subsystem, assembly or can be a part of the main system.

- DP — Discardable secondary item replaced in an LRU, SRU, PRU or SPRU at LEVEL2 and 3.
- ASSY — An assembly is ignored in the logistics breakdown, but it is used here to gather the costs from its subsystems, on the level 2 of the CBS. An ASSY can only be part of the MAINSYSTEM, according with this model definition.
- SUBSYST — A subsystem is ignored in the logistics breakdown, but it is used here to gather the cost from its components, on the level 3 of the CBS.
- PRU — Partially repairable primary item replaced directly in the system. PRUs are still not used in the model. All PRU must be converted to LRUs.
- SPRU — Partially repairable secondary item replaceable in a LRU, SRU, PRU or SPRU at LEVEL2 or 3 SPRU are still not used in the model. All SPRU must be converted into SRUs.

- QTYPM — Quantity per Mother item; QTYPM contains the number of identical items per mother item in the breakdown structure. The mother item can either be the main system, a subsystem, an assembly or another (repairable) item. The given value must be an integer ≥ 1. Default value is 1.
- PRICE — The unit price is an input parameter given per item, per system, per resource or resource position. The value is mandatory per item but optional for systems and resources. The PRICE column is included in the input tables MtrlData and should be entered as a positive float number in $1000 \times$ euro. As the name unit price suggests, it is assumed that all prices are constant irrespective of item, system or resource quantities. The price used in the model do not includes storage costs. PRICE must not be specified for ASSY items. Any value specified for an ASSY is ignored with a warning.
- FRT — Failure Rate - the failure rate is an input parameter that contains the number of failures per million hours of operation. This value is mandatory per item and can also be given per system. It is given in the input table and should be entered as a floating-point value > 0. The entered value reflects the rate per each individual item/system. The rate per item is not strictly per failure but should include all replacements including those of type “no fault found”, etc. The total sum of the sub item failure rates must not exceed the failure rate of the item/system itself. This will result in an error message during the calculation test. A total sub item failure rate less than the FRT of the item/system itself is allowed. The residual FRT in this case corresponds to failures that can be repaired without any sub item replacement. The FRT for systems is optional. If not entered this value is calculated as the sum of the item failure rates. FRT must not be specified for items having TYPE = ASSY or SUBSYST. Any value specified for an ASSY is ignored.

4.2.2.3.2 Corrective Maintenance (CM)

Corrective maintenance and the actions related to CM are usually associated with the FRT/Mean Time Between Failure (MTBF). The failure rates can be estimated for each important part of the main system. The engineering methodology tries to establish relationships between the system’s failure rates and the costs generated by those failure rates. The model in CATLOC is trying to follow the methodology and gives the opportunity to the user to fill up the data available in different ways. In the model there are two actions considered to belong to the CM: replacement and repair actions.

4.2.2.3.3 Replacement data

The replacement data concerns only replacements due to corrective maintenance. Generally a replacement may be related to any replacement action performed at any level of maintenance. A replacement action can be a replacement of a repairable primary item (i.e., an LRU or DU) and in that case the replacement takes place at OLM or a replacement of a faulty repairable secondary item or discardable, which means that the replacement action takes place either at ILM or DLM or even at CLM.

Usually a replacement refers only to replacement actions regarding primary repairable items. This statement can lead to the impression that we search replacement data only at the OLM level. This is only partially true. In fact the model is not looking at all to the replacements at the OLM level performed by the personnel at OLM level since those actions are included in crew's maintenance capability and are already captured in the remuneration of the crew.

Due to the nature of the system, most certainly some replacements of important and/or expensive items can only be performed at ILM, DLM, or CLM, i.e., when the main system is in harbour. Even less expensive items, but difficult to replace, demanding extensive working time and/or a large number of workers can be interesting to follow. The data are the events when a replacement action is needed to be performed at the OLM level, but by personnel other than the crew.

The input parameters needed for the calculations are:

- LRE is the STID where the replacement for a corrective maintenance action takes place.
- MTTRP Mean time to replace [h].
- NMTRP Number of personnel needed for replacement.
- CMRP Average cost for materiel consumption at replacement [thousands of euros].
- CMTRP Average cost for transportation due to replacements.
- ACMC is an application factor (an optional column) given per item and is used as a factor on the FRT describing the average fraction of the failure rates which leads to replacements actions performed by external personnel. This mean that the CMTC cost will be applied here.
- ACMRP is an application factor (an optional column) given per item and is used as a factor on the FRT describing the average fraction of the failure rates which leads to replacements actions performed by personnel from NME aboard, or at a foreign harbour. This mean that the transportation cost will be added here.
- CMRPC is the average cost per item for external personnel including the costs for consumables.
- CMRPCC InputParameters table - the average cost of consumables (for replacements action due to CM) consumption per year.
- MHCCMRP average man hour cost for replacement actions performed by NME.
- TRCCMRP an average cost value for transportation events per year due to CM actions.
- CMRPEX is the average cost per year for external personnel including the cost for consumables.

If the LRE is at the OLM level and the replacement action is performed by the crew, then only CMRP should be entered. If the CMRP value is not known for each of the units replaced on board, then an average cost for materiel consumption at replacement per unit of time at the level OLM should be entered for the parameter CMRPCC.

As we assumed before, in case CM actions are necessary during the mission time, not all replacements at OLM can be performed by the crew. Such replacements are supposed to be performed by the Marinebedrijf (Navy Maintenance Establishment - NME) or by other external personnel or contractors hired for this purpose.

All of these actions are understood to be performed on board, but either when the ship is at home harbour or in a harbour elsewhere. If the replacement is performed by the NME personnel then at least parameters MTTRP and NMTRP above should be specified. In lack of data, an average man-hour cost for such actions should be entered for the parameter MHCCMRP. If the replacements are performed by external personnel or contractors (LRE = CLM) and the CMRPC is unknown per unit, then an average cost per year can be given to the parameter CMRPEX.

If the action takes place at a foreign harbour, then an average cost for transportation of the personnel as well as for the unit replaced (back and forth) can be specifically given in the column CMTRP, in the input sheet MtrlData or as a general value for the parameter TRCCMRP on the InputParameters sheet. The value in the InputParameters is an average value for transportation events per year valid for all the units, where the column CMTRP has a Y (yes) and not a numerical value.

The model is computing the average cost for replacements per year according to the formula:

$$\begin{aligned} &= QTYPM \times FRT \times UTILF \times 0.00876 \\ &\quad \times ((CMRP + ACMC \times (CMTC - CMRP) \\ &\quad + ACMRP \times (MHC2 \times NMTRP \times MTTRP + CMTRP)) \,, \end{aligned} \tag{12}$$

or

$$\begin{aligned} &= QTYPM \times FRT \times TO \times 0.000001 \\ &\quad \times ((CMRP + ACMC \times (CMTC - CMRP) \\ &\quad + ACMRP \times (MHC2 \times NMTRP \times MTTRP + CMTRP)) \,. \end{aligned} \tag{13}$$

The formula is calculated per year for each unit in the material breakdown structure. The results can then be aggregated at a subsystem level or for each assembly and finally for the entire main system.

The formula also takes into consideration the operational profile described above. The results can then be shown per unit/subsystem/assembly/system and year. Note that the formula above is similar, but not the same, to the one used in the model.

The results based on these parameters, give the user many possibilities to aggregate the input data. Not all of them are described or implemented in the model, but there is however some aggregates which were implemented more for descriptive reasons because no data could be delivered by the RNLN in the MtrlData sheet.

4.2.2.3.4 Repair data

Repair data refers to the repair actions performed at all levels of maintenance on LRU or SRU. The data does not include the repair actions performed during the scheduled maintenance periods. A repair action is mainly regarded here as a replacement of an SRU or DP in an LRU or other SRU, which already was removed from the main system. Because of this characterization, there are similarities between replacement and repair input data. The following parameters are used:

- LCM STID of repair action.
- MTTR Mean time to repair MTTR [h]. It is the turnaround time, in hours by default, per repair action that does or does not require sub item replacement, i.e. all the repair actions triggered by the failure rate.
- NMTR Average number of personnel required per repair action.
- CMCM Average cost for material consumption (consumables) during a corrective maintenance task [thousands of Euros].
- CMCMC Average cost for a repair action if performed by contractor /supplier on CLM [thousands of Euros].
- CMCMCC InputParameters table -the average cost of consumables (for replacements action due to CM) consumption per year.
- MHCCMR Average man hour cost for repair actions performed by NME.
- CMCMEX Average cost per year for external personnel including the cost for consumables.

The description is similar to that presented for replacements: Focus here is on the repair actions performed by NME or the contractor. This means that LCM should be ILM, DLM or CLM. If the repair action is performed by NME, then both a cost for labour and materiel consumption will be computed. Each repair action can trigger a demand for spare parts in stock. However such demands are not captured in the model.

If the repair is performed by personnel of the NME, then at least parameters MTTR and NMTR above should be specified. In case there is a lack of data, an average man-hour cost for such actions should be entered for the parameter MHCCMR. If the CMCM value for all of the units repaired is unknown, an average cost for materiel consumption for repair actions performed by NME per suitable unit of time should be entered for the parameter CMCMCC.

If the repairs are performed by the contractor (LCM = CLM), no other value than the default value should be entered for MTTR and NMTR. Also if the CMCMC per unit is unknown, then an average cost per year can be entered for the parameter CMCMEX. CMCMC or CMCMEX should also include the transportation costs (back and forth) for the repaired unit.

On the FRT, no application factor, describing the average fraction of the failure rates which leads to repairs actions performed by the contractor, is used.

4.2.2.3.5 Preventive maintenance data

Major preventive maintenance (PM) periods on the main system are defined in the input data as a 3-years maintenance period and a 6-years maintenance period. These periods follow the calendar time during the system's life span as is shown in Figure 4 below. Cost data for these actions was acquired from the RNLN and implemented in the model.

Other types of PM can be decided by the contractor. These periods can refer to the whole system or only to subsystems or LRUs. Information on such PM periods can be entered in the input table MtrlData.

		1998	1999	2000
1		2001	2002	2002
	1	2003	2004	2005
2		2006	2007	2009
	2	2010	2011	2012
3		2013	2014	2015
	3	2017	2018	2019
4		2020	2021	2022
	4	2023	2024	2025
5		2026	2027	2028

Figure 4: Preventive maintenance periods

The PM actions include replacement and repair actions. But the model calculates the cost of a PM action as a whole; no differentiation is being made between replacements and repairs as in CM case. The parameters used are:

- LPM — STID for the PM task - should be B, C or D.
- NYPM — Number of PM actions per year.
- TPM — Preventive maintenance duration - gives the average number of labour hours for the PM task performed by one person.
- NMPM — Number of personnel necessary to perform the PM action within the required time frame (TPM).
- CMPM — The average cost for materiel consumption during PM task, costs for replacement of SRU/DP are not included [thousands of Euros].
- CPTC — Average cost for PM on LRU/SRU if performed by contractor/supplier. This also includes potential transportation costs to and from the contractor's site [thousands of Euros].

Many other costs may result from PM actions such as administrative costs or transportation costs. In order to keep the model fairly simple, but still useful for its purpose, the choice was made not to take into consideration such costs.

4.2.2.3.6 Support and test equipment

No data available. No assumptions made.

4.2.2.3.7 Spares Parts Consumption

A yearly cost for replenishment concerning the spare parts was supplied by the RNLN and implemented in the model.

4.2.2.3.8 Modifications and restorations

No data available. No assumptions made.

4.2.2.3.9 Industrial Logistic Support

No data available. No assumptions made.

4.2.3 Indirect Support

For the indirect support cost, the following data was obtained and implemented in the model:

- Materiel costs generated by Navy Command (Headquarters, Personnel & Operations).
- Man hour costs generated by Navy Command (Headquarters, Personnel & Operations).

5.0 COST NORMALIZATION

For the parametric and analogy methods, U.S. ship data was pulled from VAMOSC, with all costs in constant fiscal year (FY) 2009 U.S. Dollars. In order to deal with the high variability of O&S costs a two steps approach was undertaken:

- Data from VAMOSC was averaged on an annual basis between different hulls in each class;
- Then, the yearly data for each class of ship was averaged over the life of the hull, in all cases beginning in 1984 and ending when the ship was either decommissioned or the end of the sample period.

For the engineering estimation, the cost normalization follows the same principles as for the acquisition cost without the complexity related to different currencies. The costs gathered from the RNLN are expressed in FY 2005 euros, and they have been converted to FY 2008 euros using the annual average index for The Netherlands obtained from eurostat. No other inflation rates or other financial indices were applied for the rest of the life span of the SoI after 2008. The only variations of the yearly costs are triggered by real input data obtained from the RNLN regarding fuel consumption and PM costs.

6.0 RESULTS AND ANALYSIS

After normalizing the cost to FY 2008 and respecting the anonymity requested not to show explicitly the ship's O&S costs, the same fictitious notional common currency (abbreviated NCC) was used as in Annex B1 related to the Rotterdam acquisition costs. This was also done to be able to include the estimate for the acquisition cost in the model and to show the full results. The value used in the model is the actual Rotterdam acquisition cost.

Table 2 shows the values expressed in the same currency for the highest cost aggregates and for the total life cycle. The rest of the results are presented in percentage.

Usually an analysis made through an LCC engineering estimate comes with a lot of details on the distribution of the costs in the materiel dimension through the system breakdown structure or on the maintenance organization, for each and every site taken into consideration. The method will try to find parts of the system or parts of the organization that are generating the highest costs in order to find a solution to the problem.

Table 2: Total O&S costs

	Cost Aggregate	O&S Costs (Million NCC)
7.1	Operation	329.8
7.2	Supporting operations	24.0
7.3	Maintenance	321.0
7.4	Sustaining Support	21.6
7.5	PHST	204.5
7.6	Restoration	0
7.7	Indirect Support	182.0
Total O&S Costs		1082.9

At the same time, it shows where the resources are consumed and which tasks are the most demanding. The methodology goes hand in hand with RAMS methods based on both optimization and simulations.

Such an analysis cannot be performed here, mostly because of the lack of data. When data is missing, the result of an engineering estimate does not generate solutions, merely it raises more questions for further analysis.

However, it is useful to present the results and then to question them. The next task is then to either dig deeper in the records and find more data, or start a short term follow-up to see if data can be improved.

With a tool like CATLOC, an analyst can dissect the data in many ways and then present the results in a meaningful manner. In this study, it was not possible to do so, as the quality of the data was not sufficient. The results presented in the following charts are at a high level of the CBS, but they are sufficient to show some problems. Figure 5 shows the distribution between the O&S cost and the acquisitions cost. Percentage values are rounded to the nearest integer. At this level the results are not extraordinary.

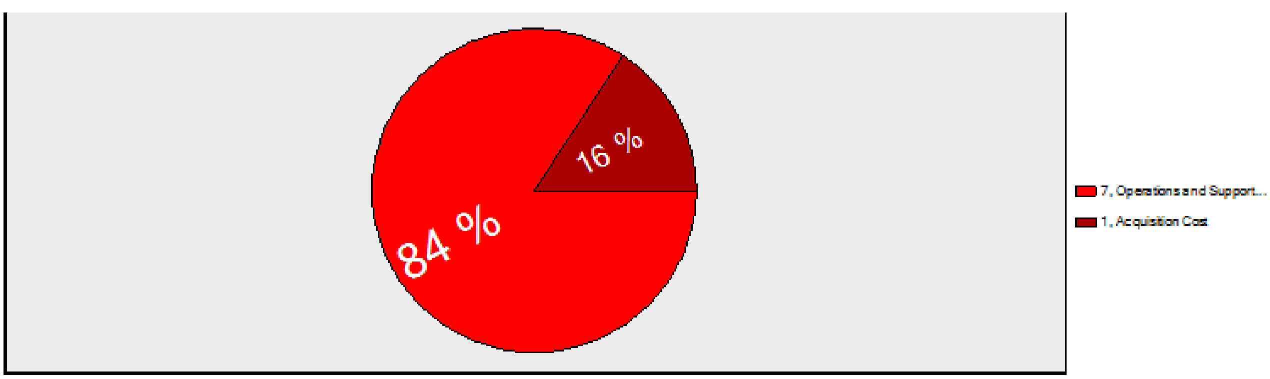

Figure 5: LCC showing O&S cost versus acquisition costs

Figure 6 shows the O&S costs in more detail. It can be noticed that the cost of Sustaining Support and Supporting Operations are relatively low to what could be expected, while the Indirect Support costs are relatively high. Additional analysis and data would be required to understand why the O&S costs are distributed over the CBS in these proportions.

Looking to the Operational costs (Figure 7), it is clear that the cost of personnel is too high when compared to the cost for fuel, oil and other lubricants. Additional analysis and data would be required to understand these differences.

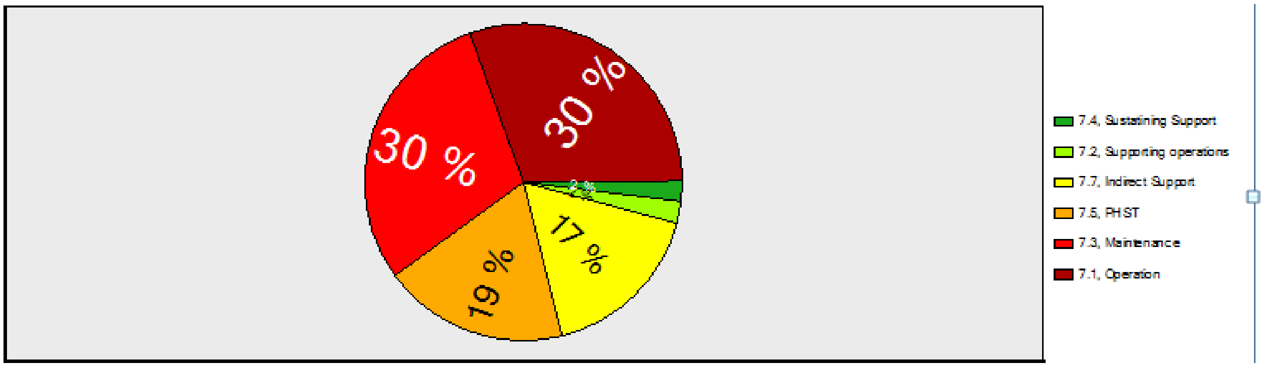

Figure 6: O&S cost distribution

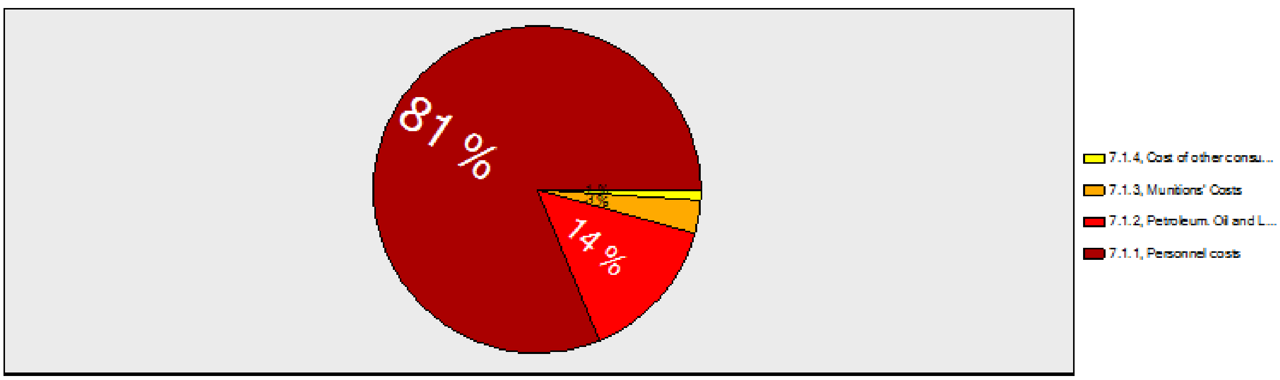

Figure 7: Distribution of operational costs

It can be noticed that the maintenance costs (Figure 8) of the two helicopters on the ship is almost as large as the ship's cost for Preventive Maintenance (PM) and Corrective Maintenance (CM) together. Furthermore, 7.3.3 (cost related to other operating systems) contains some uncertainties (e.g., whether the helicopters fuel cost is included or not). Given that the data was taken from the RNLN financial system, it was difficult to get additional information to clearly define the scope of this cost.

It is possible to breakdown the analysis further and to keep on asking questions, however, these questions should be asked directly to the user of the system.

Figure 9 shows the distribution of the PM costs (materiel and personnel) over time: 7.3.1.1 (the lower part of the bars) represents man-hour costs and 7.3.1.2 (the upper part of the bars) represents materiel costs. Figure 10 shows the distribution of cost over the types of resources used in operation.

Finally, this section presents the sensitivity of the estimate to changes in the parameter values. All parameters are increased by 100% and the impacts of that increase on the total O&S cost are shown in Figure 11. The parameters are ranked relatively to their impact on the O&S cost. It is noted that average yearly income of operators (MIOP), number of operators on-board (NOPT) and number of helicopters (NHALO) are

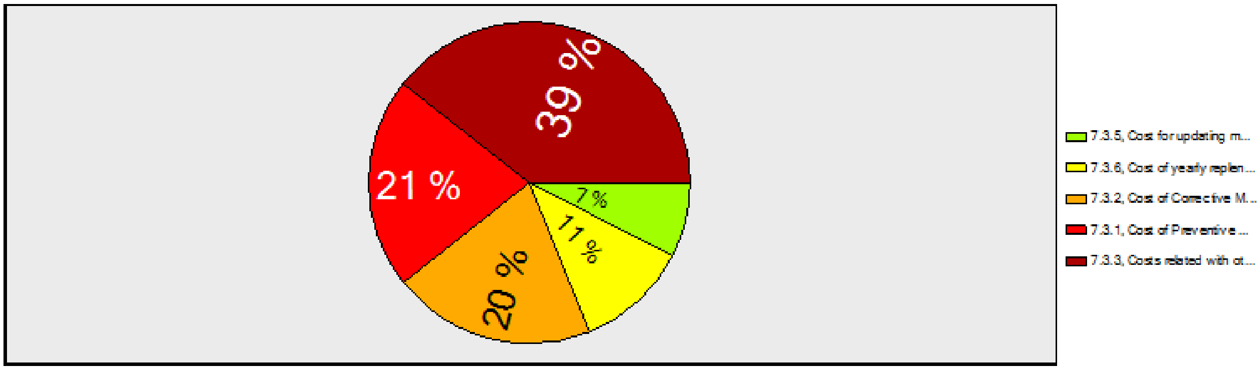

Figure 8: Distribution of maintenance costs

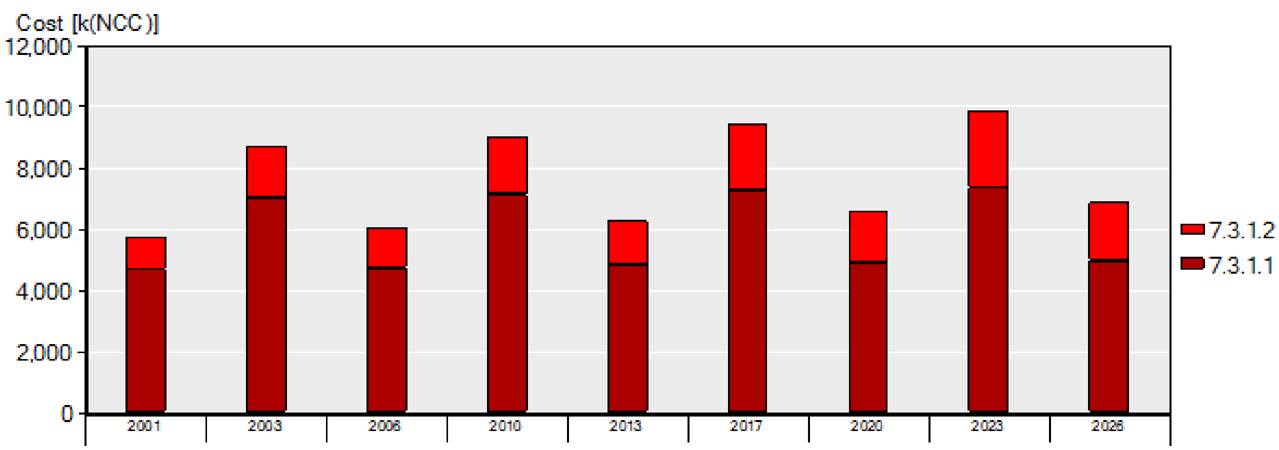

Figure 9: Preventive maintenance costs over time

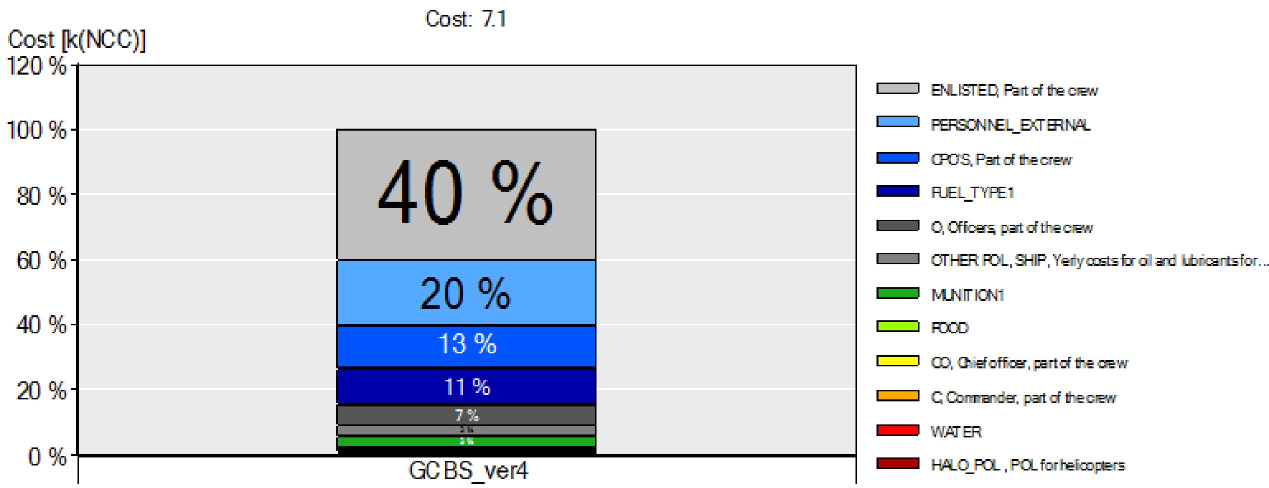

Figure 10: Distribution of cost over resource types

the three parameters that will influence total O&S cost the most, given an equally large percentage change, but the differences are not large.

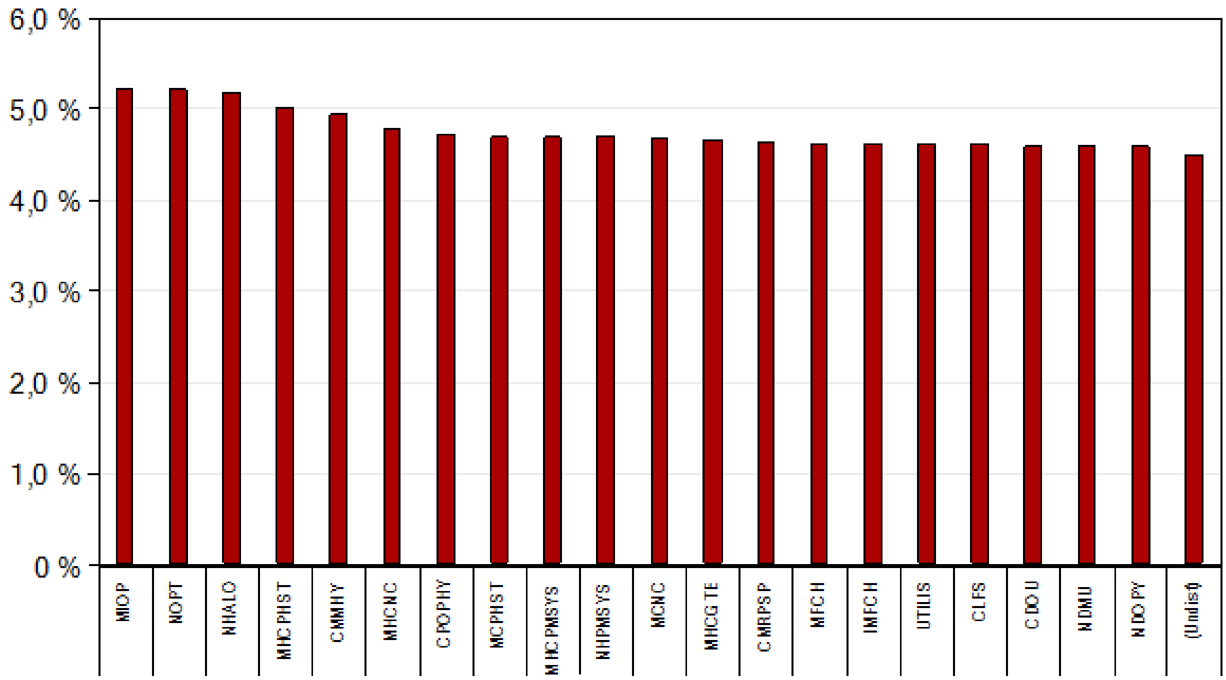

Figure 11: Sensitivity analysis over all parameters

The CM actions are usually a major cost driver for the O&S total cost. Because of the commercial sensitivity of data, the RNLN was not able to provide any data concerning CM. In general, it is considered that for large military systems, the acquisition cost stands for just under 30% of the total LCC and the O&S cost for the rest.

Usually maintenance, i.e., PM and CM actions stands for about just under 50% of the O&S cost. Frequently the costs for CM are not bigger than the costs for PM. Of course in the above figures both personnel and materiel cost are included.

7.0 COMPARING CAIG AND GCBS MODELS

The main objective of this section is to compare the top-down approach represented by the **CAIG model**, developed at the U.S. Naval Center for Cost Analysis, with the bottom-up approach represented by the **GCBS model**. The two cost models resulting from applying these approaches are presented in the appendices 1 and 2 of this report. However, in this section, a closer look is given to their set up.

The comparison has been made only for Rotterdam since the GCBS calculations have only been performed for this ship. No data was available for Johan de Witt.

The tasks have been mainly to work on the cost structures of the two models in order to make them comparable. The main tasks were:

- Implement the two cost structures in CATLOC with some restructuring of the GCBS model;
- Compare the results of the both approaches.

7.1 Analysing the Models

The basic structures of both models are shown in Figure 12:

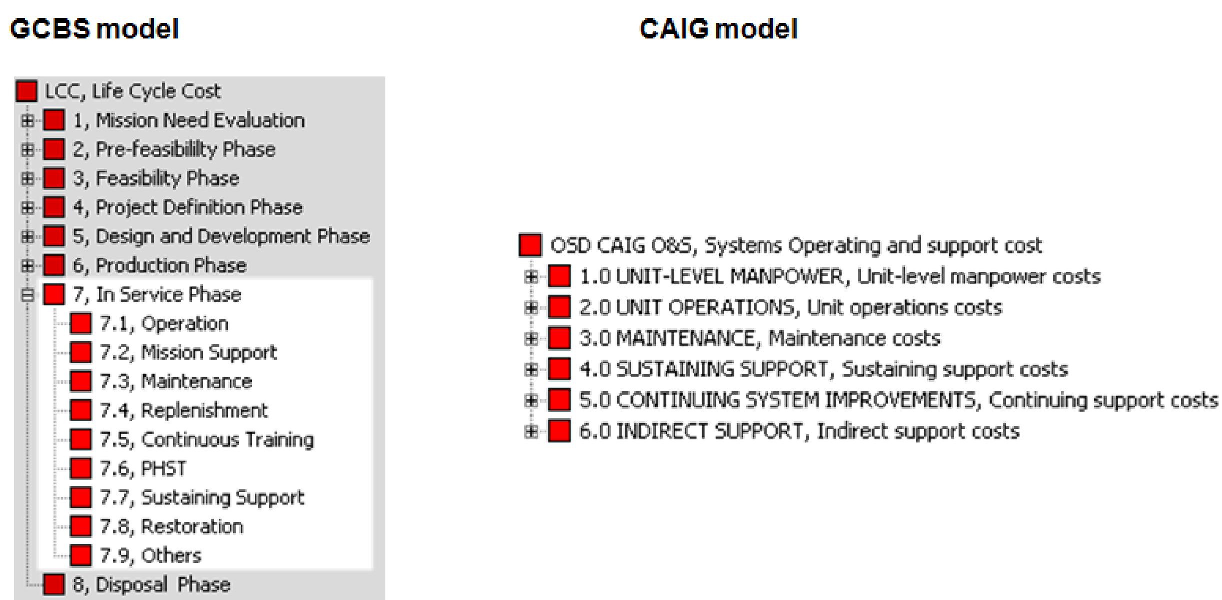

Figure 12: Structure of CAIG and GCBS models

In order to achieve the main objective of the analysis: to compare and evaluate the two cost estimating methods, the models needed to be implemented in CATLOC and to be made as comparable as possible. Given that the Cost Breakdown Structure of the GCBS model was more granular than the CAIG model, it was decided to restructure the former to make the comparison easier. The resulting model is called **GCBS-CAIG model** and the Cost Breakdown Structure is presented in Appendix 3. During the GCBS model Cost Breakdown Structure restructuring, some assumptions were made. These assumptions are not specifically presented here but can be easily understood by comparing the GCBS-CAIG model (the transformed GCBS model) presented in Appendix 5 with the original model from Appendix 1. For example:

- Cost of test and support equipment and tools has been moved from Maintenance to Sustaining Support to match the CAIG model, even if its value is nil in the original GCBS model.
- Materiel and Man-hour costs for handling of Government Owned Stores have been moved to Sustaining Support too.

As for the implementation of the CAIG model in CATLOC, the initial intention was to implement the second Level of Cost Elements in the structure hierarchy (see Appendix 4) and then populate these costs. However, this was not achieved due to the lack of the definitions of these costs.

After the restructuring of the GCBS model Cost Breakdown Structure and the implementation of the CAIG model in CATLOC, the actual comparison can be done by mapping the cost elements in the GCBS-CAIG model to the relevant cost aggregate in the CAIG model for which an estimate exists (see Figure 13 for an example of the principle). This will allow for an assessment of the differences between the estimates. Big differences should trigger further investigations on the possible reasons for the deviation. In particular, to enable a fair comparison it was necessary to identify any costs that were present in the CAIG model but not in the GCBS model and vice versa.

7.2 Results

The final results are shown in Figure 14:

The total O&S costs computed exclude costs associated with CAIG cost work breakdown elements 5.0 (Continuing System Improvements) and 6.0 (Indirect Support). The main reason was that too much uncertainty existed to match some costs to these aggregates. Another reason is the total absence of CAIG 5.0 in the GCBS model and CAIG 6.0 in CAIG estimates.

7.3 Discussion

Due to the lack of data and information, no conclusions could be drawn on the accuracy of the models. Therefore, the observations made in this section are completely based on a qualitative analysis of the two models:

- Aggregate O&S costs in the GCBS-CAIG model are not directly comparable to the CAIG model. Although the CAIG model focuses on operations and support, it also includes, for instance, costs for continuous testing and development. In the GCBS, these costs belong to the aggregate “Production phase”, which is not part of the O&S. Furthermore, the CAIG model is not intended for crisis/war scenarios, while in the GCBS model (as implemented in CATLOC) a war/crisis scenario could easily be handled by considering it as a mission type.
- The “personnel costs”, which were considered to be overestimated in the CAIG model, are more than 30% higher in the GCBS model. However, the sum of CAIG elements 1.0 and 2.0 together seems to be close to the GCBS equivalent.

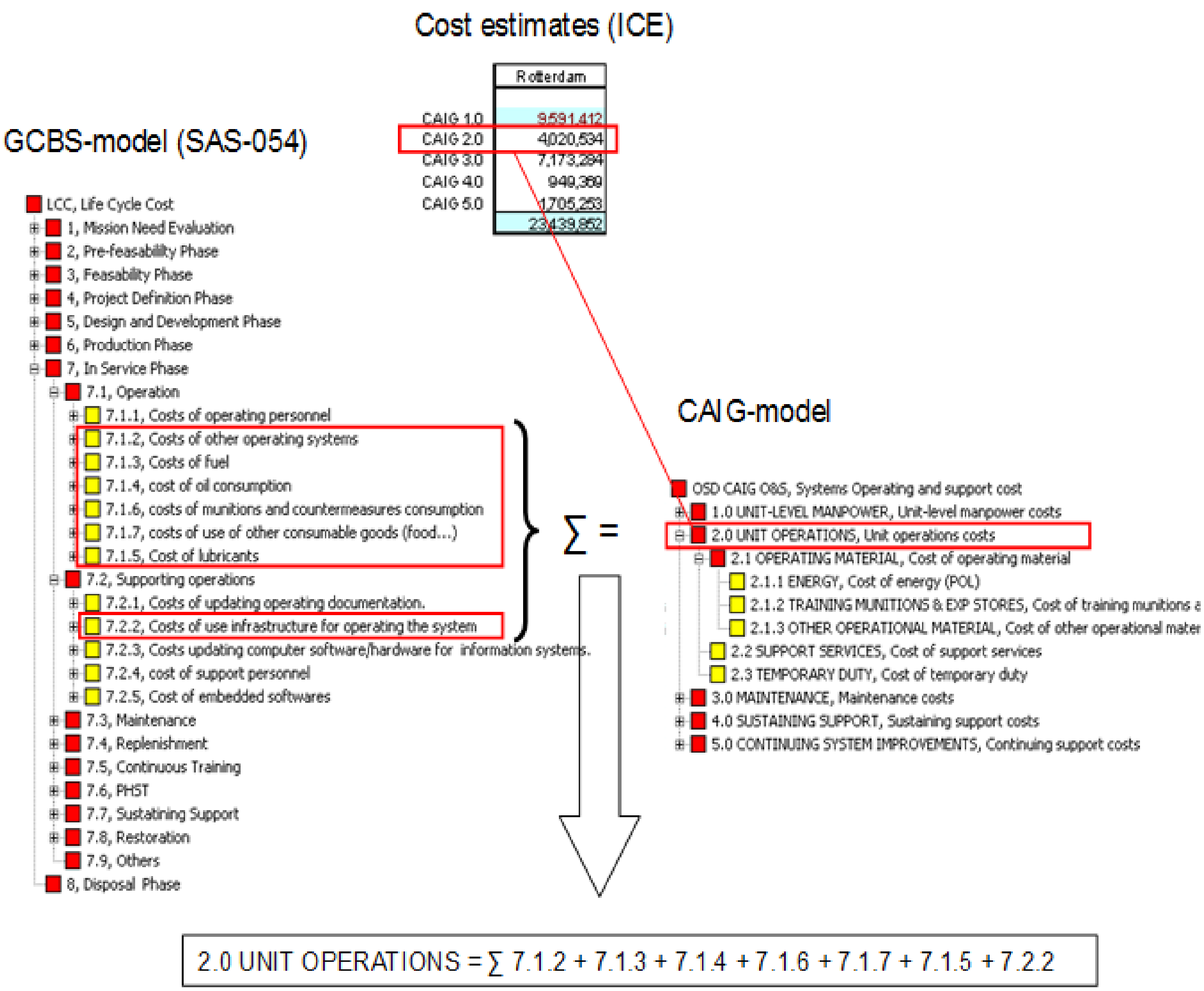

Figure 13: Example of the comparison method

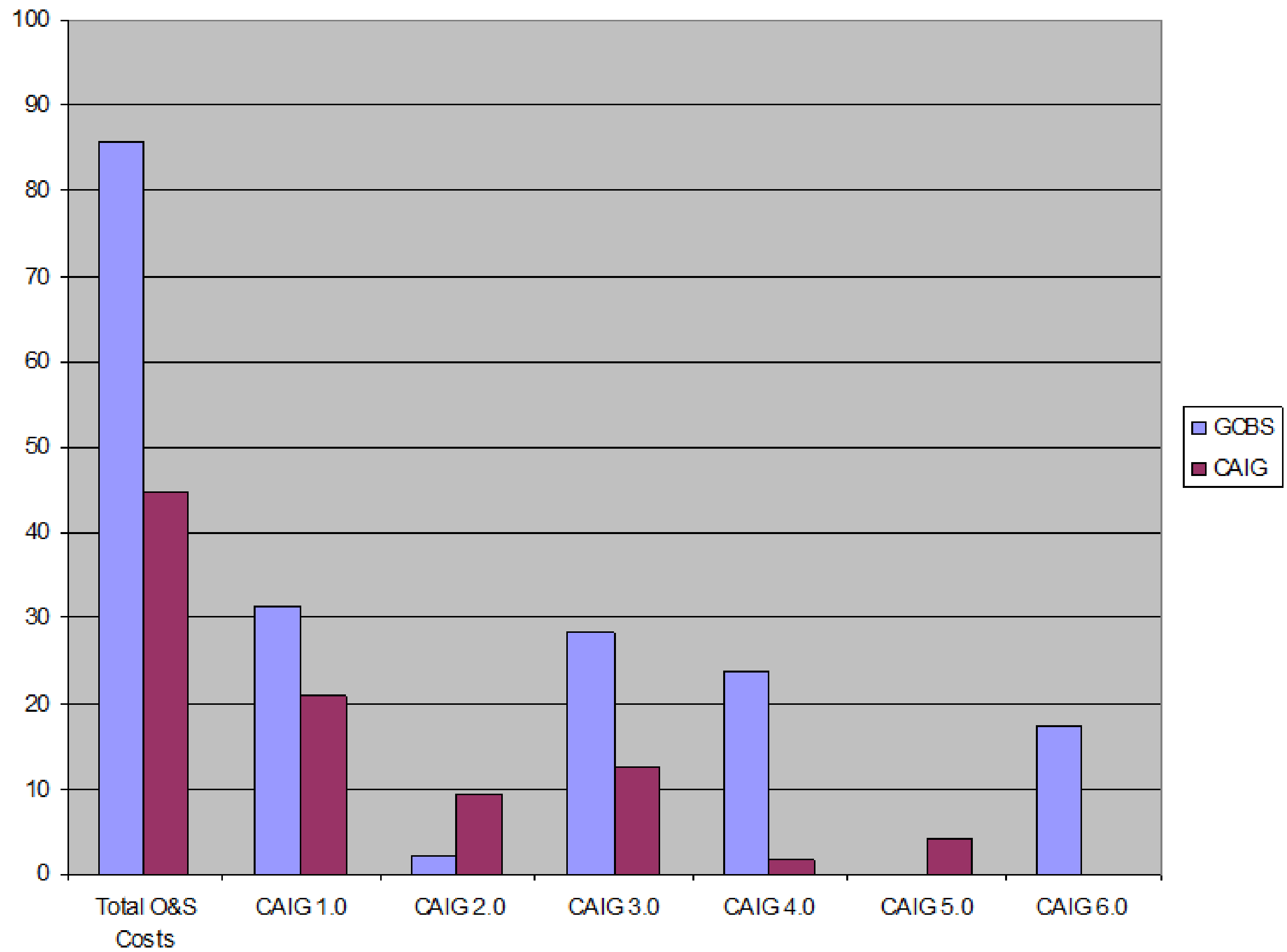

Figure 14: GCBS vs. CAIG

- The “maintenance costs” are more than twice as high in the GCBS model. If we consider only the PM costs, they still are higher. CAIG element 4.0 should be excluded from the comparison because there’s obviously something wrong there.

Without more data it is not possible to draw any conclusions on which of the methods produces the most reliable cost estimate. Still, even if it has not been possible to do a numerical evaluation, it is clear that the GCBS model is more relevant than the CAIG model when it comes to understanding the origin of the costs.

If the only objective is to get the total sum of all costs, a thorough investigation may show that the two methods are more or less equivalent. If, on the other hand, the purpose of the cost analysis is to find cost drivers, identify opportunities for savings, or help decision-makers investment decisions, the bottom-up approach should be used.

8.0 LESSONS LEARNED

The section is divided into seven parts: the general management of the estimating process and the feedback of each topic of the cost estimating process; aims and cost boundary; data and assumptions; methods, models and tools; risk and uncertainty; analysis of the results; and presentation of results.

8.1 General Management of the Estimating Process

8.1.1 Initial Plan

SAS-076 started with a plan describing the activities and captured this in a Project Initiation Document (PID). Originally it was described as follows:

For the acquisition stage, a top-down approach would be adopted, using the information in the DADD and applying the parametric method. As a second estimating method, it was possible to apply the analogy method using public available data (Internet, NAO(UK) reports, etc.).

Initially the cost-estimating approach consisted of two iterations. The first iteration was to estimate high-level cost elements of the cost breakdown structure. This would result in many assumptions; these assumptions would need to be checked by the RNLN. It would then have been used to identify cost drivers. The second iteration was to go into more details for the costs drivers, if additional data was available.

The main milestones for the first iteration were:

- Milestone 1: Agreement on cost elements to be calculated - 16/01/2009.
- Milestone 2: Release of the data and assumptions list - 26/06/2009.
- Milestone 3: Release of first report - 22/01/2010.

The main Milestones for the second iteration were:

- Milestone 4: Agreement on new cost elements to be calculated - 22/01/2010.
- Milestone 5: Release of the updated data and assumptions list - 09/07/2010.
- Milestone 6: Release of second iteration report - 01/10/2010.

8.1.2 Actual Implementation of the Initial Plan

The following steps were actually followed after having established the PID:

- Agreement on the Cost Breakdown Structure (CBS): follow ANEP 41 (SWBS) and the CBS from SAS-054 report;
- Developed a Data and Assumptions Document Definition (DADD) based on the data found in public sources, participant's inputs and the RNLN;
- Investigated software tools to be used.
- Decision on methods to be use for O&S: analogy, parametric and engineering.

Since the O&S costs for a materiel system are in high extent dependent on both the use of the system as well as the systems reliability and maintenance, the group decided to apply a bottom-up/engineering method to estimate the O&S costs. The group proposed to use the type of estimating approach the Swedish Material Defence Administration has experience on. This approach was mainly applied to evaluate alternatives in acquisition, maintenance optimization, improvement of the in-service cost effectiveness, etc. Sweden also provided the necessary computer tools to support the O&S cost estimate. The analysis was dependent on the provision of the necessary input data by the RNLN. Since both the Rotterdam and the Johan de Witt have been used and maintained for quite some years, the availability of data was expected to be high.

8.1.3 Lessons Identified

- The group did not work continuously on this project, causing additional challenges in the estimates and in the management of some important issues.
- The SAS-076 group considered the estimating guideline and the tasks described in SAS-054 of the management process to be useful.
- The group tried to follow the SAS-054 guidelines as much as possible, however the group was restricted by the limited availability of resources and competence available in the group or available within the group members' professional network. This affected, to a certain extent, the work process. The conclusion was that the SAS-054 guidelines could be followed, however, it takes time and resources. Therefore, the resources and the budget required to do an estimate according to the SAS-054 guideline should be carefully planned before the actual work starts.

8.2 Definition of the Aims and Cost Boundary

8.2.1 The Team's Approach

The customer for the results of the study was the RNLN. As this estimate is also used to apply the guideline developed by SAS-054, NATO RTO can be considered as a secondary customer.

The aim was to practice the guidelines of SAS-054. The objective for the O&S costs estimation was to approximate the yearly in-service support costs and to sum them for a chosen life-time given the planned operational profile. This would result in finding the major cost drivers and eventually give the RNLN some opportunities to improve their maintenance plans.

For the O&S costs, the cost boundary changed during the cost estimating process, e.g., helicopters were first not included. The Rotterdam group included the costs for the helicopters as the RNLN informed the group that these costs were included in the data. Originally the disposal costs were included in the Cost Breakdown Structure, but the RNLN could not provide a strategy for the disposal of the ships, which resulted in the removal of these costs from the Cost Breakdown Structure.

8.2.2 Lessons Identified

- The aim and the objective of the study are fundamental for the way the cost analysis is conducted.
- For this ICE the generic Cost Breakdown Structure, as defined in the SAS-054 Report, was used and considered to be useful. The cost elements were estimated were defined iteratively.

8.3 Data and Assumptions

8.3.1 The Team's Approach

It was decided to use three approaches to estimate the O&S costs: parametric, analogy approach (CAIG estimate), and the engineering bottom-up approach.

A first estimate for the O&S costs was made using O&S cost data retrieved from VAMOSC (Visibility and Management of Operating & Support Costs) data base. The CBS followed OSD Cost Analysis Improvement Group (CAIG) Cost Element Structure, which provides a standardized system to prepare and submit O&S cost estimates. Analogous ships were selected on the basis of: dimensions, ship technical characteristics, and intended role/mission. Data was then averaged over the life-time of the ship, and the data points were used as a basis for the cost estimating relationships (CERs). Two estimating methods were used to compute the CAIG elements: a parametric approach – using only one parameter for each CAIG element, and an analogy method using LSD-49 Class averages. The outcome from both methodologies was then combined, leading to an initial cost estimate for the O&S costs.

The engineering approach to estimate the O&S cost is to a great extent based on the connection between Reliability, Availability, Maintainability and Supportability data (RAMS), and costs for spare parts, man-hours and other cost elements. The costs are computed in the cost atoms algorithms in the cost model. For this, it is important to have detailed knowledge of the technical and organizational data. Since the group could not obtain the required reliability data to estimate the costs for corrective maintenance (mainly failure rates), it was not possible to calculate the costs according to the engineering method. This is of great importance and had a severe impact on accuracy of the cost estimate since the Corrective Maintenance (CM) is often a major cost driver in the in-service phase of a system. As a result, a combination of CAIG data and Swedish experience with respect to the fraction of CM cost related to the total O&S cost was used instead. Naturally the purpose was to have a full estimate of the O&S cost, but data availability to apply the engineering method was insufficient

For this O&S estimate, the generic Cost Breakdown Structure, as defined in the SAS-054 Report, was used. The cost elements that were estimated were defined iteratively. The methodology defined in the SAS-028 Report with the generic Resources, Product and Task dimensions was used. Also, the definition of the generic System Breakdown Structure, ANEP41, was used. If necessary, these approaches were tailored according to the specifics of the program. For this assessment, the O&S costs were estimated using both organizational and operational data, as well as technical and financial data. Data was gathered by the RNLN. A more detailed description of the data can be found in the Section 4 and Appendix 1 of this Annex.

Regarding the cost normalization for the parametric and analogy methods used in CAIG estimate, the data was taken from the VAMOSC database with all costs in constant fiscal year (FY) or base year 2009 U.S. Dollars. In order to deal with the high variability in O&S costs, a two step approach was undertaken:

- Data from VAMOSC was averaged on an annual basis between different ships in each class;
- Then the yearly data for each class of ship was averaged over the life-time of the ships in all cases beginning in 1984 and ending when the ship was either decommissioned or at the end of the sample period.

The costs for the engineering method, provided by the RNLN in euros base year 2005, were normalized using the eurostat labour index and converted to euros base year 2008.

8.3.2 Lessons Identified

- Lessons learned related to the CAIG estimate:
  - Using a single parameter to estimate costs may not produce reliable estimates. For example CAIG elements 3 & 4 are computed on a more or less accurate relationship between displacement and maintenance/sustainment costs. The maintenance methods and schedules should also be taken into account here.
  - CER (cost estimating relationships) with FLD (Full load Displacement) only works when ships being compared have similar manning, operational and maintenance philosophies.
  - The best way to predict fuel consumption is to have specific data on steaming hours, fuel costs, engine efficiency and the units' usage portfolio.
  - System complexity, number of systems and many other factors can all have an impact on costs.
  - Databases like VAMOSC are very useful to estimate O&S costs.
- Lessons learned related to the engineering method:
  - Access to Follow-Up data from the In-Service phase was a necessary condition to be able to apply the engineering method for estimating O&S costs. If that condition could not be fulfilled, rough assumptions would have to be made. An alternative, not performed for the current estimation, was to use parametric COTS models to complete the estimate.
  - One has to bear in mind that the engineering method allows you not only to calculate the costs themselves, but also the costs related to the specific system and its operational profile and support organization. The engineering method allows the user to vary the above mentioned data and to calculate the costs for this variation. Thus, the engineering method allows the user to determine the cost efficiency of the system. This implies that the method is considered to be both expensive and vulnerable. The latter implies its dependence of accurate Follow-Up and RAMS data. This has been exemplified by the fact that the group was not able to gather all the necessary data.

8.4 Methods, Models and Tools

8.4.1 The Team's Approach

Three methods were used: an Engineering bottom-up, a parametric, and an analogy approach. However, it appeared that the engineering bottom-up was not applicable as such due to the lack of engineering data such as reliability of the items. The engineering method used was rather a mix of top-down and bottom-up methods.

The tools investigated were mainly commercial. It was not possible to acquire one of the tools, due to the very limited resources available. Therefore the group used tools that were already available in one or more nations and for which a temporary licence was given to the participating nations (CATLOC).

8.4.2 Lessons Identified

- The data available determined, to a very large extent, the choice of methods, from the start of the cost analysis process to the end of it. It was a continuous interaction between choices of methods, computer models and availability of data. For example, the methodologies were chosen assuming that certain data would be available, however, some data was not available and forced the team to adapt the methodology, or to gather the data from a different source.

- The SAS-054 report discusses the engineering method (bottom-up). The description of the engineering method is correct, however, reliability data should be mentioned explicitly. Suggestions include adapting the following sentence: “This type of estimate is used when detailed design data, such as reliability data on the system, is available”.

- Furthermore, the engineering method is not the same as a bottom-up approach. Handbooks (including SAS-054) mix-up approaches (top-down and bottom-up), and methodologies (parametric, engineering). Top-down and bottom-up are dependent on the granularity of the Cost Breakdown Structure and the available data. What is missing in the SAS-054 report is the specification of the top-down and the bottom up approaches, before detailing the types of methodologies.

8.5 Risk and Uncertainty Analysis

8.5.1 The Team’s Approach

Most data was received from the RNLN and was considered reasonably accurate. However, some parameters collected outside of the RNLN have uncertainties attached to them. These are: fuel price, labour cost escalation and the cost elements for which it was not possible to obtain data.

8.5.2 Lessons Identified

When applying an engineering method, it is inevitable that some data are uncertain. As a result, there is a need to adjust collected data to the LCC model for the analysis in question. The way to handle these uncertainties is to conduct a sensitivity analysis or to apply Monte Carlo simulation. For this study, this was not done.

8.6 Analysis of Results

8.6.1 The Team’s Approach

The team showed the results for both the CAIG CBS and the GCBS. The engineering method (GCBS) allows showing detailed results and the distribution of costs among the cost aggregates and cost atoms. This way cost drivers can be identified and more detailed analysis on costs can be started. However, because of the lack of data, this type of analysis could not be performed.

8.6.2 Lessons Identified

Although sufficient data was not available to perform a detailed analysis on the costs, it was useful to present the results as detailed as possible. This way, areas can be identified for further detailed analysis. Furthermore, the CATLOC model proved to be very useful when applying the engineering method and provided very useful graphical outputs.

Another lesson is that showing the features of a model can be used as a catalyst for further data collection. Once customers are aware of what type of analysis is possible with a certain model, they are more than willing to gather more detailed data.

8.7 Presentation of the Results

8.7.1 The Team's Approach

Intermediate results were shown to the RNLN with the intention of persuading them to gather more data. This was done by explaining why the extra data was required and what was possible if data was to be provided. This was part of the "learning process" included in the methodology. Both the cost estimator and the operator of the system were learning from each other. The first one was learning what the user wants how the system was operated and structured and the second learns why it was necessary to capture costs, what the relation was between the RAMS data and the costs and finally how he could improve the effectiveness of his system.

8.7.2 Lessons Identified

- The SAS-076 task group did unintentionally assume that the data provided by the RNLN was coherent with the CBS, which was not the case. This could be regarded as a typical mistake of an international study group or an example of how input data determines the method. Therefore, during the acquisition phase of a system, the prerequisites for gathering data necessary to the future cost estimations should be established. This means that follow-up databases and input data structures should be implemented very early.

- Even if the group could not obtain the data necessary to properly apply the engineering method, and did not get the desired outcomes, the method worked. The learning process discussed above instigated a sharp reaction within the RNLN. They have already decided to improve the ways they collect data for future cost estimates.

9.0 CONCLUSIONS

The Rotterdam group managed to produce an estimate for the O&S costs based on the planned operational profile. Success depended on the availability of the right expertise, the right computer tools, and the right data sources. For the latter, especially for O&S cost estimation, open sources were helpful but any estimator cannot solely rely on them.

The engineering method used to estimate cost in a budgeting process, especially from a historical perspective, was not an optimal approach. Concerning budgeting and financing it is often required that all the costs should be presented, and for that more appropriate economical methods already exist. However, the engineering method is a very powerful tool, if not the only one, to identify and reduce cost drivers during the critical decision making in the systems lifetime.

The engineering method should concentrate on the objective of the analysis the user and the cost estimator would like to achieve. The boundaries for work, type of data, amount of data, the design of the CBS etc., differ according to the type of analysis. For example, not all the costs or RAMS parameters influence the analysis to be used. The engineering method is trying to minimize the need of input data taking into consideration only those costs and related parameters which influence the decision making process.

It is probably better to look at the engineering method as an on-going enterprise during the system life time, i.e., “from cradle to grave”. Applied properly and consistently, the method not only implicitly leads to improvement of the system efficiency, but also gives the system operator after a period of time, access to a database similar to VAMOSC which will substantially improve the future Life Cycle Cost estimations.

The cost estimate resulting from this study should be considered as indicative. All the uncertainties related to the operating profiles during the system lifetime, the reliability, maintainability and supportability issues, the impacts of future technology, and the economical fluctuation on the market in general are reasons to believe that an accurate estimate of the life cycle costs is unfeasible. However, alternative solutions can usually be evaluated with higher degrees of consistency by certifying that the levels of uncertainty are similar for all considered alternatives. The engineering method may come closest to reality.

10.0 REFERENCES

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Appendix B2-1: CATLOC LCC MODEL DESCRIPTION

Figure 15 shows how the LCC-tree can be viewed in CATLOC.

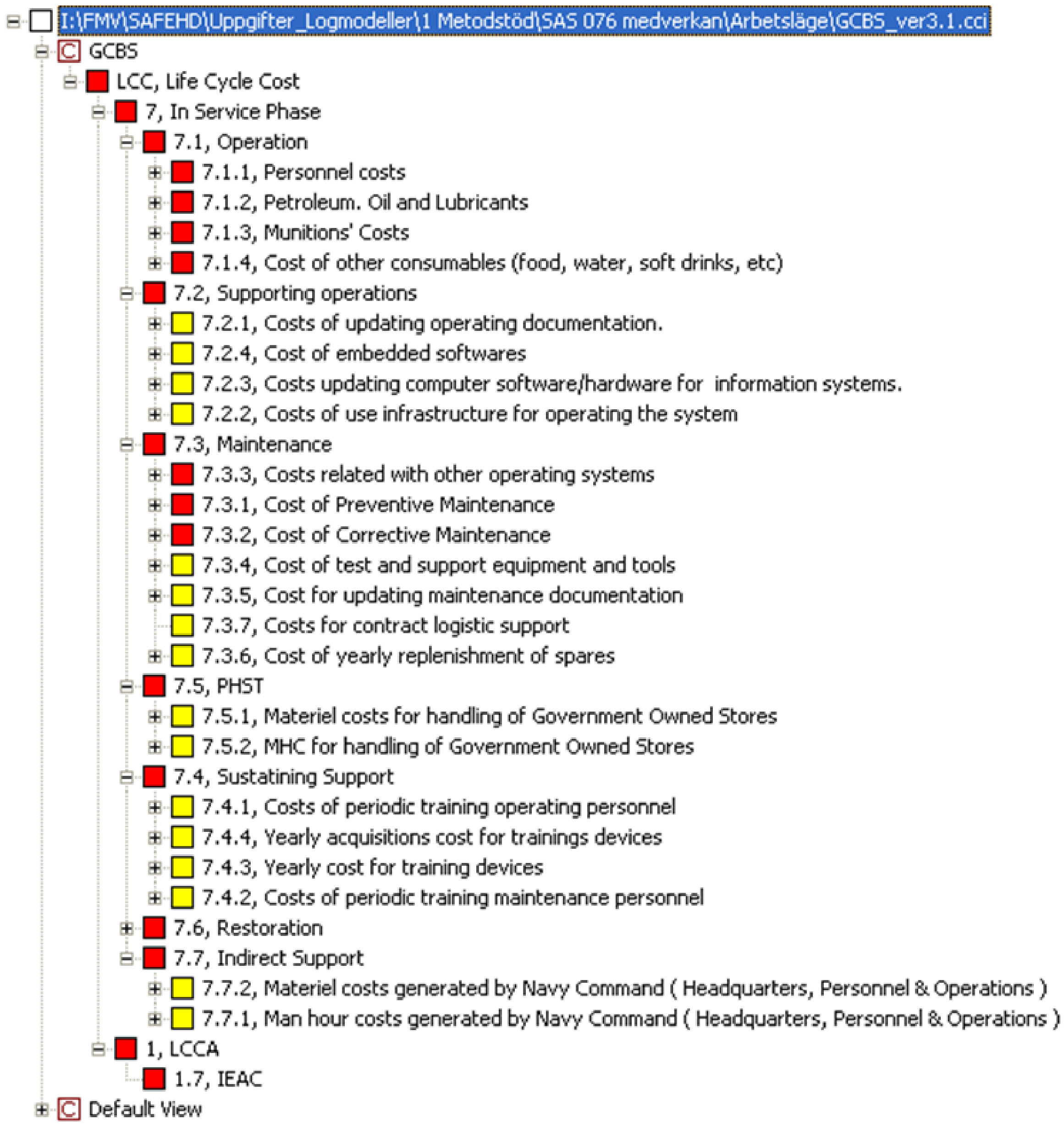

Figure 15: The LCC tree as listed in the CATLOC model

The CATLOC model shown in Table 3 below is based upon a template implementing a generic cost break-down structure (GCBS) proposed by the NATO RTO Task Group SAS-054. The generic hierarchy is described in section 10.3 and 12.1 of the SAS-054 final report. The template includes cost aggregates and a cost structure but no formulæ, cost atoms or domain dimensions.

The model was populated with cost atoms according to the initial assumptions made by SAS-076, and after that it was adjusted and tailored using the data obtained from the RNLN. Some cost aggregates, or cost atoms, have been kept in the model even if input data was not available. The main reason for this was to illustrate the benefits the engineering LCC methodology has if data was available. During a demonstration session these benefits were shown to the RNLN. The RNLN decided to have a closer look at the model and eventually decided to obtain the necessary data to perform a complete analysis.

The cost aggregates in Tables 3 – 5 comprise the sum of the cost aggregates or cost atoms from the next lower level. A cost atom is usually described by a parameter or a formula. For a better understanding of the model, first a “Level report” (Tables 3 – 5) is shown, representing the relation between cost aggregates and cost atoms. Then a “Tree report” (Tables 6–10) is shown, revealing the description of the parameters used in the formulæ. In both tables, the Title/Index column gives the name of the LCC tree node. In the Level report only, the cost aggregates have a formula (a sum) on the row below the description.

Table 3: The CATLOC model A1-1 Level reporting table (Levels 0–2)

Level	Title/Index	Description
LEVEL 0		
	LCC	Life Cycle Cost
		7 + 1
LEVEL 1		
	7	In Service Phase
		7.1 + 7.2 + 7.3 + 7.5 + 7.4 + 7.6 + 7.7
	1	LCCA
		1.7
LEVEL 2		
	7.1	Operation
		7.1.1 + 7.1.2 + 7.1.3 + 7.1.4
	7.2	Supporting operations
		7.2.1 + 7.2.2 + 7.2.3 + 7.2.4
	7.3	Maintenance
		7.3.1 + 7.3.2 + 7.3.3 + 7.3.5 + 7.3.4 + 7.3.6 + 7.3.7
	7.4	Sustaining Support
		7.4.1 + 7.4.2 + 7.4.3 + 7.4.4
	7.5	PHST
		7.5.2 + 7.5.1
	7.6	Restoration
		7.6.1
	7.7	Indirect Support
		7.7.1 + 7.7.2
	1.7	IEAC

Table 4: The CATLOC model A1-1 Level reporting table (Level 3)

Level	Title/Index	Description
LEVEL 3		
	7.1.1	Personnel costs 7.1.1.1 + 7.1.1.2
	7.1.2	Petroleum, Oil and Lubricants 7.1.2.1 + 7.1.2.2 + 7.1.2.3 + 7.1.2.4 + 7.1.2.5
	7.1.3	Munitions' Costs 7.1.3.1
	7.1.4	Cost of other consumables (food, water, soft drinks, etc) 7.1.4.1 + 7.1.4.2 + 7.1.4.3 + 7.1.4.4
	7.2.1	Costs of updating operating documentation
	7.2.2	Costs of use infrastructure for operating the system
	7.2.3	Costs updating computer software/hardware for information systems
	7.2.4	Cost of embedded software
	7.3.1	Cost of Preventive Maintenance 7.3.1.1 + 7.3.1.2 + 7.3.1.3 + 7.3.1.4 + 7.3.1.5
	7.3.2	Cost of Corrective Maintenance 7.3.2.1 + 7.3.2.2 + 7.3.2.3
	7.3.3	Costs related to other operating systems 7.3.3.1 + 7.3.3.2
	7.3.5	Cost for updating maintenance documentation
	7.3.4	Cost of test and support equipment and tools
	7.3.6	Cost of yearly replenishment of spares
	7.3.7	Costs for contract logistic support
	7.5.2	Man-Hour cost for handling of Government Owned Stores
	7.5.1	Materiel costs for handling of Government Owned Stores
	7.4.1	Costs of periodic training operating personnel
	7.4.2	Costs of periodic training maintenance personnel
	7.4.3	Yearly cost for training devices
	7.4.4	Yearly acquisitions cost for trainings devices
	7.6.1	Cost of recommended and mandatory modifications of the system
	7.7.1	Man hour costs generated by Navy Command (Headquarters, Personnel Operations)
	7.7.2	Materiel costs generated by Navy Command (Headquarters, Personnel & Operations)

Table 5: The CATLOC model A1-1 Level reporting table (Levels 4-5)

Level	Title/Index	Description
LEVEL 4		
	7.1.1.1	Costs of operating personnel
	7.1.1.2	Average personnel costs for operation of helicopters
	7.1.2.1	Cost of fuel
	7.1.2.2	Cost of oil consumption
	7.1.2.3	Cost of lubricants
	7.1.2.4	Yearly costs for POL, Ship
	7.1.2.5	Average POL costs due to maintenance of helicopter per year
	7.1.3.1	Costs of munitions and countermeasures consumption
	7.1.4.1	Average cost for food per year
	7.1.4.2	Average yearly cost for water consumption
	7.1.4.3	Average yearly cost for electricity consumption
	7.1.4.4	Average yearly cost of "other operational material"
	7.3.1.1	Annual man hour costs for major preventive maintenance action on main system
	7.3.1.2	Materiel costs for major preventive maintenance action on main system
	7.3.1.3	CHPMR, Annual man hour costs for PM actions on unit level
	7.3.1.4	CMPMT, Annual materiel costs for PM actions on unit level
	7.3.1.5	CPMTC, Annual costs for PM actions on unit level performed by contractor
	7.3.2.1	Average CM costs due to unit replacement actions 7.3.2.1.1+7.3.2.1.2+7.3.2.1.3+7.3.2.1.4+7.3.2.1.7+7.3.2.1.8 +7.3.2.1.5+7.3.2.1.6
	7.3.2.2	Average CM costs due to unit repair actions 7.3.2.2.1 + 7.3.2.2.2 + 7.3.2.2.3 + 7.3.2.2.4 + 7.3.2.2.5
	7.3.2.3	Average yearly CM cost , both material and man power
	7.3.3.1	Average man-hour cost for maintenance of helicopters (maintenance staff)
	7.3.3.2	Average materiel costs due to maintenance of helicopter per year
LEVEL 5		
	7.3.2.1.1	CHCMRP, Man hour costs for unit replacements due to CM during operational time onboard the ship performed by NME at OML level
	7.3.2.1.2	CMCMRP, Average cost for materiel consumption (consumables) due to CM replacement actions at OML performed by the crew
	7.3.2.1.3	CTCMRP, Average cost for transportation due to CM replacement action at OLM performed by NME personnel abroad
	7.3.2.1.4	CCMRPEX, Average cost for CM replacements at unit level performed by external personnel
	7.3.2.1.7	TRCCMRP, CMRp - Average transportation costs for replacements actions due to CM at OLM performed by personnel from NME per year - includes personnel and replaced unit transportation back and forth
	7.3.2.1.8	CMRPEX, CMRp - Average cost for replacement actions if performed by contractor / external man-power at OLM
	7.3.2.1.5	CMRPCC, CMRp - Average cost of consumables consumption for replacements due to CM at OLM per year
	7.3.2.1.6	MHCCMRP, CMRp - Average man-hour cots for replacements due to CM at OLM performed by personnel from NME per year
	7.3.2.2.1	CCMRNME, Average CM costs for repair actions at unit level performed by NME per year
	7.3.2.2.2	CMCMCT, Average CM costs for repair actions at unit level performed by contractor per year
	7.3.2.2.3	CMCMCC, CM - Average cost of consumables for repair actions due to CM per year
	7.3.2.2.4	MHCCMR, CM - Average man-hour cots for repair actions due to CM per year
	7.3.2.2.5	CMCMEX, CM - Average cost for repair actions due to CM per year performed by contractor

In Tables 6–10 in the Description column, the first row corresponds with the title of the node. The next row provides the formula used, if applicable. Then the parameter used is described. In some cases the parameter used is the result of a calculation. In this case the formula is shown below the parameter description. Finally the row before the next node is reserved for remarks. The sum for cost aggregates is no longer shown.

Table 6: The CATLOC model A1-2 Tree reporting table

Title/Index	Description
7	In Service Phase
7.1	Operation
7.1.1	Personnel costs
7.1.1.1	Costs of operating personnel
	NOPT*(MIOP+COPC)
	NTOPP - Number of different types of operational personnel. Not used explicitly in the model
	NOPT - Number of operators per type (manning profile)
	MIOP - Average yearly income of operators (salaries + benefits)
	COPC - Average yearly cost of on-board personnel uniforms, accessories, shoes, special clothing, etc
7.1.1.2	Average personnel costs for operation of helicopters
	NHALO*CPOPHY
	NHALO - Number of Helicopters on the ship
	CPOPHY - Average personnel costs for operation of helicopters
7.1.2	Petroleum, Oil and Lubricants
7.1.2.1	Cost of fuel
	CLFS*MFCH*UTILIS*8.760
	NFT - Number of types of fuel consumed per system per mission. The model allows 2 types of fuel
	MFCH - Average fuel consumption/operational hour/type of fuel in litres (l)
	IDFUEL - Unique identifier for fuel type
	IDMISSION - Unique identifier for mission type
	IMFCH - RNLN, input data , fuel consumption per year
	CLFS - Average cost for fuel per type of fuel in 1000*EUR/l
	RNLN input
7.1.2.2	Cost of oil consumption
	MOCH*CLOS*UTILIS*8.760
	NOT - Number of types of oil used per system per mission
	MOCH - Average oil consumption per operational hour per type of oil
	An analogous formula as for the fuel consumption is used for the oil consumption. However, since these cost atoms are not used, the formula and its parameters are not presented here.
	CLOS - Average cost for oil consumption per operational hour per type of oil used
	NOT is defined in CATLOC explicitly in the materiel domain, ALL_OIL_TYPES which contains for the moment 2 types of lubricants OIL1 & OIL2 No costs are calculated here, as the oil consumption is unknown
7.1.2.3	Cost of lubricants
	MLCH*CLGS*UTILIS*8760
	NLT - Number of types of lubricants used per system per mission
	MLCH - Average lubricant consumption per operational hour per type of lubricants
	Analogous formula as for fuel consumption is used for the lubricants consumption but since these cost atoms are not used, the formula and its parameters are not presented here.
	CLGS - Average cost for lubricants consumption per operational hour per type of lubricants
	NLT is defined in CATLOC explicitly in the materiel domain, ALL_LUBRICANT_TYPES which contains for the moment 2 types of lubricants LUBRICANT1 & LUBRICANT2. No costs are calculated here, as the lubricant consumption is unknown.
7.1.2.4	Yearly costs for POL, Ship
	CPOLSH
	CPOLSH - Average cost for POL, ship
	In this case the formula is just an input parameter.
	RNLN input
7.1.2.5	Average POL costs due to maintenance of helicopter per year
	NHALO*CPOLHY
	CPOLHY - Average POL costs due to maintenance of helicopter per year
	RNLN input

Table 7: The CATLOC model A1-2 Tree reporting table (Cont'd)

Title/Index	Description
7.1.3	Ammunition Costs
7.1.3.1	Costs of ammunition and countermeasures consumption MMCY*CMUY **MMCY** - Average units of ammunition type i consumed per year **CMUY** - Average cost per unit of munitions type i More than one type of ammunition can be defined (RNLN input)
7.1.4	Cost of other consumables (food, water, soft drinks, etc)
7.1.4.1	Average cost for food per year NMOB*CFOB*UTILF*365 **NMOB** - Number of man on-board the ship **CFOB** - Average cost of food per person per day Assumed cost, see section 4
7.1.4.2	Average yearly cost for water consumption CWCU*MWCY **CWCU** - Average cost per water unit **MWCY** - Average water consumption per year Assumed cost. See section 4
7.1.4.3	Average yearly cost for electricity consumption CECU*MECY **CECU** - Electricity cost per kWh **MECY** - Average electricity consumption per year No data available, not used.
7.1.4.4	Average yearly cost of "other operational material" CCOE **CCOE** - Yearly cost of "other operational material" No data available, not used.
7.2	Supporting operations
7.2.1	Costs of updating operating documentation. NDOU*NDOPY*CDOU **CDOU** - Cost per operating documentation update of type i per year **NDOU** - Number of operating documentation updates for each type per year. **NDOPY** - Number of operating documentation updates of type i per year Only CDOU has an assumed input defined in section 4 representing the total cost per year for documentation updates.
7.2.2	Costs of use infrastructure for operating the system NDFH*CDFH **NDFH** - Period in harbours per year **CDFH** - Average fee in harbour per day Not enough data available, not used
7.2.3	Costs updating computer software/hardware for information systems. No data available, not used
7.2.4	Cost of embedded software No data available, not used
7.3	Maintenance
7.3.1	Cost of Preventive Maintenance
7.3.1.1	Annual man hour costs for major preventive maintenance actions on main system MHCPMSYS*NHPMSYS **MHCPMSYS** - Man hour costs for major preventive maintenance actions on main system **NHPMSYS** - Number of labour hours for major preventive maintenance actions on main system RNLN input RNLN input
7.3.1.2	Materiel costs for major preventive maintenance actions on main system **MCPMSYS** RNLN input

Table 8: The CATLOC model A1-2 Tree reporting table (Cont'd)

Title/Index	Description
7.3.1.3	Annual man hour costs for PM actions at unit level. **CHPMR** NYPM*QTYPM*TPM*NMPM*MHC The formula mentioned above is just to illustrate how this cost atom may be computed. The formula does not work in the model as the parameters should be defined as vectors or arrays over predefined domains. See section 4 for definition of the parameters. Kept in the model for demonstration reasons.
7.3.1.4	**CMPMT** NYPM*QTYPM*CMPM Annual materiel costs for PM actions at unit level. See 7.3.1.3.
7.3.1.5	Annual costs for PM actions at unit level performed by contractor **CPMTC** IF(LPM=1,NYPM*QTYPM*CPTC,0) See 7.3.1.3.
7.3.2	Cost of Corrective Maintenance
7.3.2.1	Average CM costs due to unit replacement actions
7.3.2.1.1	Man hour costs for unit replacements due to CM during operational time onboard the ship performed by NME at Organisational level. **CHCMRP** MHC*QTYPM*FRT*ACMRP*NMTRP*MTTRP The formula mentioned above is just to illustrate how this cost atom may be computed. The formula does not work in the model as the parameters should be defined as vectors or arrays over predefined domains. See section 4 for definition of the parameters. Kept in the model for demonstration reasons.
7.3.2.1.2	Average cost for materiel consumption (consumables) due to CM replacement actions at Organizational level performed by the crew. **CMCMRP** UTILF*0.00876*QTYPM*FRT*(1-ACMC)*CMRP It Is the aggregate value for all the parts which has a value for CMRP and where LRE is OLM The same comments as above.
7.3.2.1.3	Average cost for transportation due to CM replacement action at OLM performed by NME personnel abroad **CTCMRP** QTYPM*FRT*UTILF*0.00876*ACMRP*CMTRP The same comments as above.
7.3.2.1.4	Average cost for CM replacements at unit level performed by external personnel **CCMRPEX** QTYPM*FRT*UTILF*0.00876*ACMC*CMRPC These costs should include both man power costs and material consumption costs The same comments as above.
7.3.2.1.7	Average transportation costs for replacements actions due to CM at OLM performed by personnel from NME per year - includes personnel and replaced unit transportation back and forth **TRCCMRP** Should be an input from the user. Kept in the model for demonstration reasons
7.3.2.1.8	Average cost for replacement actions if performed by contractor / external man-power at OLM **CMRPEX** Should be an input from the user. Kept in the model for demonstration reasons
7.3.2.1.5	Average cost of consumables consumption for replacements due to CM at OLM per year **CMRPCC** Should be an input from the user. Kept in the model for demonstration reasons
7.3.2.1.6	Average man-hour cots for replacements due to CM at OLM performed by personnel from NME per year **MHCCMRP** Should be an input from the user. Kept in the model for demonstration reasons
7.3.2.2	Average CM costs due to unit repair actions

Table 9: The CATLOC model A1-2 Tree reporting table (Cont'd)

Title/Index	Description
7.3.2.2.1	Average CM costs for repair actions at unit level performed by NME per year **CCMRNME** 0.00876*UTILF*QTYPM*FRT*(MHC*NMTR*MTTR+CMCM) The above formula is just to illustrate how this cost atom may be computed. The formula does not work in the model as it is because the parameters should be defined as vectors or arrays over predefined domains. Se Ch.4 for parameters definitions. Kept in the model for demonstration reasons
7.3.2.2.2	Average CM costs for repair actions at unit level performed by contractor per year **CMCMCT** QTYPM*FRT*UTILF*0.00876*CMCMC The same comments as above.
7.3.2.2.3	CM - Average cost of consumables for repair actions due to CM per year **CMCMCC** Should be an input from the user. Kept in the model for demonstration reasons
7.3.2.2.4	CM - Average man-hour cots for repair actions due to CM per year **MHCCMR** Should be an input from the user. Kept in the model for demonstration reasons
7.3.2.2.5	CM - Average cost for repair actions due to CM per year performed by contractor **CMCMEX** Should be an input from the user. Kept in the model for demonstration reasons
7.3.2.3	Average yearly CM cost, both material and man power **AYCMC** Average yearly cost for CM actions This cost is calculated as a result of the assumption made in Ch. 4
7.3.3	Costs related with other operating systems
7.3.3.1	Average man-hour cost for maintenance of helicopters (maintenance staff) NHALO*MHCOPH **MHCOPH** - Average man-hour cost for maintenance of helicopters (maintenance staff) Input data from RNLN
7.3.3.2	Average materiel costs due to maintenance of helicopter per year NHALO*CMMHY **CMMHY** - Average materiel costs due to maintenance of helicopter per year Input data from RNLN
7.3.5	Cost for updating maintenance documentation NDMU*NDMY*CDMU **NDMU** - Number of maint. documentations updates for each type per year NDMY - Number of maint. documentations updates of type i per year CDMU - Cost for one maint. documentation update of type i per year No data available. Not used
7.3.4	Cost of test and support equipment and tools CTSEQ+CITSEQ **CITSEQ** - Yearly investment cost for test/support equipment **CTSEQ** - Yearly support cost for test/support equipment No data available. Not used
7.3.6	Cost of yearly replenishment of spares **CMRPSP**
7.3.7	Costs for contract logistic support No data available. Not used
7.5	PHST
7.5.2	MHC for handling of Government Owned Stores **MHCPHST**
7.5.1	Materiel costs for handling of Government Owned Stores **MCPHST**
7.4	Sustaining Support

Table 10: The CATLOC model A1-2 Tree reporting table (Cont'd)

Title/Index	Description
7.4.1	Costs of periodic training operating personnel NTC_OP*NTP_OP*CTC_OP+CTOPCY CTC_OP - Cost for one op. training course of type i per attendee including the necessary documentation CTOPCY - Annual cost for training material (consumables) for operating personnel [cost/year] **NTC_OP** - Number of op. training courses for each type per year **NTP_OP** - Number of attendees per op. training course of type i No data available. Not used
7.4.2	Costs of periodic training maintenance personnel NTC_MAINT*NTP_MAIN*CTC_MAINT+CTMCY **CTC_MAINT** - Cost for one maint. training course of type i per attendee including the necessary documentation **CTMCY** - Annual cost for training material (consumables) for maintenance personnel [cost/year] **NTC_MAINT** - Number of maint. training courses for each type per year **NTP_MAIN** - Number of attendees per maint. training course of type i No data available. Not used
7.4.3	Yearly cost for training devices CTD*SUM(NTD,ALL_TRAININGS) **NTD** - Number of training devices of type k used for training courses /year **CTD** - Average cost for using a device of type k once No data available. Not used
7.4.4	Yearly acquisitions cost for trainings devices CATD*NTDA **CATD** - Annual investments in training devices of type k **NTDA** - Number of training devices acquired per year No data available. Not used
7.6	Restoration
7.6.1	Cost of recommended and mandatory modifications of the system No data available. Not used
7.7	Indirect Support
7.7.1	Man hour costs generated by Navy Command (Headquarters, Personnel & Operations) **MHCNC**
7.7.2	Materiel costs generated by Navy Command (Headquarters, Personnel & Operations) **MCNC**
1	LCCA Life Cycle Cost Aq.
1.7	**IEAC** Assigned for independent estimated acquisition cost

Appendix B2-2: EX ANTE TESTING – CAIG

PURPOSE

The purpose of this study was to develop a cost estimating relationship methodology that could be used to estimate the Operating and Support (O&S) cost for the Dutch Navy Landing Platform Dock (LPD) Rotterdam (L-800) and Johan de Witt (L-801) ships[5]. The basis for the methodology was the use of the U.S. Naval Visibility and Management of Operating and Support Costs (VAMOSC) [5] management information system. VAMOSC collects and reports U.S. Navy and U.S. Marine Corps historical weapon system O&S costs. VAMOSC provides the direct O&S costs of weapon systems, some linked indirect costs (e.g., ship depot overhead), and related non-cost information such as flying hour metrics, steaming hours, age of aircraft, etc.

DATA

General data specifications for the L800 and L801 were provided by Study Director Dr. Brian Flynn. The information was verified to be accurate via Jane's and open-source information from the internet. U.S. ship data was pulled from VAMOSC, with all costs in constant fiscal year (FY) 2009 dollars. Additional information was taken from the Naval Vessel Registry [6], which is the official inventory of U.S. ships and service craft from the time of vessel authorization through its life cycle and disposal. Initially, O&S data was pulled for the following ships: LCC-19, LHD-1, LPD-1, LPD-4, LPD-17, LPH-2, LSD-36, LSD-41, LSD-49 and LST-1179. Ultimately, LCC-19, LHD-1, LPH-2 and LST-1179 were dropped from the data set because the dimensions of these classes were not analogous to the L800 and L801. LPD-17 was dropped because there were only 2-years of data available for that class. Therefore, the ships classes used in the final dataset were:

$$\mathbf{LPD-1} \qquad \mathbf{LPD-4} \qquad \mathbf{LSD-36} \qquad \mathbf{LSD-41} \qquad \mathbf{LSD-49}\,.$$

To deal with the high variability of O&S costs between hulls, classes and years, two steps were taken. First, data was averaged on an annual basis between the different hulls in each class. This was done so as to provide a better estimate of the annual O&S costs for each class. Although some ships of a class may experience abnormal costs from year to year, when averaged together this volatility should be mitigated. The yearly data for each class of ship was then averaged over the life of the hull, in all cases beginning in 1984 and ending when the ship was either decommissioned or the end of the sample period (2008) was reached. Again, this was done to deal with the high variability of O&S costs. It is noted that the presented methodology can be used to estimate the average annual O&S costs of a hull, not the specific O&S costs in a given year.

PARAMETRIC COST ESTIMATING RELATIONSHIP METHODOLOGY

The parametric method is based on various characteristics or measurable attributes of the system, hardware and software being estimated. It depends upon the existence of a causal relationship between system costs and these attributes. Such relationships, known as CERs (cost estimating relationships) are typically estimated from historical data using statistical techniques.

[5]This appendix is an exact copy of the report: Methodology for Approximating Annual Operating Support Cost of Amphibious Ships - Dutch Navy Landing Platform Dock Rotterdam (L800) and Johan de Witt (L801) by Michael Mender and John Murray of the U.S. Naval Center for Cost Analysis [4].

The methodology behind the creation of the CERs for each Cost Analysis Improvement Group (CAIG) cost element was as follows.

- First, analogous ships to Rotterdam and Johann de Witt were selected and their data pulled from VA-MOSC.
- The work breakdown structures (WBS) for each element were analysed so as to identify likely cost drivers for each element.
- Possible drivers were then analysed via scatter plots to evaluate the relationship between the probable drivers and their respective CAIG elements.
- If a correlation was revealed, regression calculations were run via the Excel module 'CoStat', to quantify the relationship and allow non-arbitrary comparisons of cost drivers.

Although other functional forms were evaluated, all of the final CERs used standard linear regression models with one variable.

The equation therefore takes the form:

$$Y = B_0 + B_1 X_1 \, , \tag{14}$$

where Y is the CAIG element being estimated (the dependent variable), B_0: is a constant term, X_1: is the identified cost driver, and B_1: is the coefficient attached to that cost driver.

CAIG 1.0 (Unit Manpower)

This CAIG element is driven by the number of personnel (billets) assigned to a ship, and personnel rates associated with each billet [7]. Billets per ship were originally identified as the main cost driver to be used in the CER, but further analysis of the data revealed that due to substantially different manning requirements between the U.S. and Dutch hulls, a regression based upon the number of billets was not feasible. The problem being that all U.S. ships that are of a similar size and function to the L-800CL had approximately 300 billets. With all the data points clustered around one number; no correlation existed to base a CER. As a result, full load displacement was selected, however, displacement only works when the ships for which the estimate is being prepared have similar manning requirements to U.S. ships. As the L-800/L-801CL don't have similar manning requirements, the recommendation was that CAIG 1.0 should be estimated using the analogous method presented later in this report.

CAIG 2.0 (Unit Operations Cost)

This CAIG element is largely driven by fuel costs. Ships that consume more fuel experience higher CAIG 2.0 costs than ships that use less fuel. The decision was made to develop a CER around annual fuel consumption. As this piece of data was not available for the L-800/L-801CL class of ships, an intermediate equation using full load displacement and a dummy variable for engine type was used to estimate annual fuel consumption. Please note that this implicitly assumes that the RNLN has a similar usage portfolio when compared to the USN, additionally it assumes that the RNLN experiences comparable engine efficiency and fuel costs.

CAIG 3.0 (Maintenance Costs)

This CAIG element was found to be largely driven by full load displacement (FLD). Larger ships cost more to maintain, therefore, a simple regression linking full load displacement to CAIG 3.0 was used to estimate the maintenance costs of the L-800 and L-801.

CAIG 4.0 (Sustainment Costs)

This CAIG element was found to be similar to CAIG 3.0. A major cost driver is FLD, and a correlation was found to exist between an increase in full load displacement and larger sustainment costs.

CAIG 5.0 (Continuing Systems Improvements)

This CAIG element is notoriously difficult to estimate. Upgrades and systems improvements can vary wildly between hulls in a class, between years for individual hulls, and are also heavily influenced by policy and other non-quantifiable factors. A variety of methods and theories were evaluated, with the following being the only one that showed any promise. It was hypothesized that ships with higher annual fuel consumption may also have higher annual CAIG 5.0 related costs. The reason we might expect to see this is that ships that consume more fuel, probably have a higher OPTEMPO and may receive higher priority for upgrades as a result. Keeping in mind that upgrades are influenced by policy and other factors, it is likely that the actual CAIG 5.0 costs for the RNLN (or any navy other than the USN) will differ significantly.

MONTE CARLO SIMULATION FOR PREDICTION INTERVALS

Once the CERs for each individual CAIG element were established, the combined information was assembled into an estimate through the use of CoStat and Crystal Ball. CoStat can be programmed to automatically generate prediction intervals when a regression is run. By setting the prediction intervals such that they were one standard deviation from the mean, the standard deviation of each estimate was easily computed via simple math. This information was then fed into Crystal Ball. Crystal Ball allows analysts to run Monte Carlo simulations, which allow for the generation of prediction intervals for the combined estimate. This is done by using the mean estimate and standard deviation for each CAIG element to create a normal distribution for that element. The combined estimate was then set equal to the sum of the most probable values of each of the elements. Crystal Ball then runs a simulation, during which random numbers are generated according to the probabilities associated with the normal distributions for each element. After 200,000 iterations, a histogram of the results reveals the most likely values of the combined estimate.

ANALOGOUS COST ESTIMATING METHODOLOGY

First, of all the classes in the available dataset, the most analogous based on its similarities in dimensions to the Rotterdam and Johan de Witt was selected. Then the analogous ratio or multiplier defined for each cost element *e* will be:

$$R_e = A_e / P_e^1 \,, \tag{15}$$

where A_e is the historical average analogous system cost corresponding to the CAIG cost element e being estimated (the dependent variable), and P_e^1 is the value of the analogous ship parameter on which the analogy will be made for the CAIG cost element e being estimated.

The estimated cost for the cost element *e* is:

$$Y_e = R_e \times P_e^0 \, , \tag{16}$$

where P_e^0 is the value of the estimated ship parameter on which the analogy will be made for the CAIG cost element *e* being estimated.

Of the five classes in the dataset, the LSD-49 Class was the most analogous based on its similarities in dimensions to the L-801 but is slightly larger than L-800.

Table 11: Ship parameters

Ship Name	Rotterdam	Johan de Witt	Harpers Ferry
Nation	Netherlands	Netherlands	United States
Number	L800	L801	LSD 49
Type	LPD	LPD	Landing Ship Dock
Dimensions			
Length(m)	162.2	176.35	185.9
Beam(m)	25	25	25.6
Draught(m)	5.9	5.9	6.3
Displacement(tonnes)			
Light	?	?	11604
Full Load	12750	16680	16601
Crew Complement			
Officers	13	17	30
Crew	100	129	309

Additionally, the LSD-49CL is the newest U.S. amphibious ships among the VAMOSC dataset, and it has a similar power train (Diesel Electric) to the L-800 and L-801. The class consists of the following hulls:

$$\mathbf{LSD-49} \qquad \mathbf{LSD-50} \qquad \mathbf{LSD-51} \qquad \mathbf{LSD-52} \, .$$

With the exception of CAIG 1.0 elements, the methodology for developing the analogous cost estimate was based on each Dutch LPD's weight relative to the LSD-49CL. For CAIG elements 2.0 – 5.0, the equation takes the form:

$$Y = A_0 \times (FLD_0/FLD_1) \, , \tag{17}$$

where Y is the CAIG element being estimated (the dependent variable), A_0 is the historical average LSD-49 class cost in CY09$ corresponding to the CAIG element being estimated, FLD_0 is the L-800 or L-801 full load displacement (tonnes), and, FLD_1 is the LSD-49CL average full load displacement (tonnes).

2-5.1 CAIG 1.0 (Unit Manpower)

The L-800 and L-801 do not have similar manning requirements. The recommendation for estimating CAIG 1.0 is to multiply the estimated number of billets with the expected personnel rates. Personnel rates were obtained by averaging the annual cost per billet for officers (O-5 to WO-2) and for enlisted (E-9 to E-1) into a composite

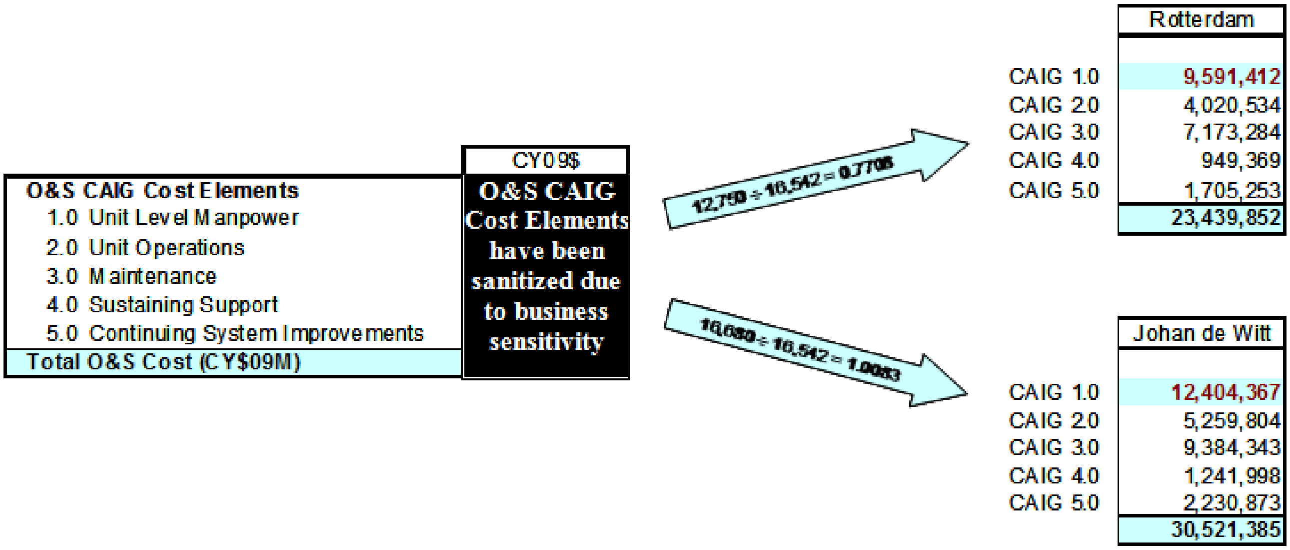

Figure 16: VAMOSC O&S cost estimate results for HMS Rotterdam and Johan de Witt

officer rate and an enlisted composite rate. These two numbers were then multiplied by the number of officer billets and enlisted billets per ship, as a means of estimating the annual unit manpower costs per ship.

Due to the significantly smaller number of billets of the RNLN ships, there will be a significant difference in CAIG 1.0 between USN and RNLN ships. The method presented in this section was designed to capture that difference as it includes the number of billets per ship, and the only assumption is that the RNLN experiences similar personnel costs.

Appendix B2-3: COST BREAKDOWN STRUCTURE FOR THE GCBS-CAIG MODEL

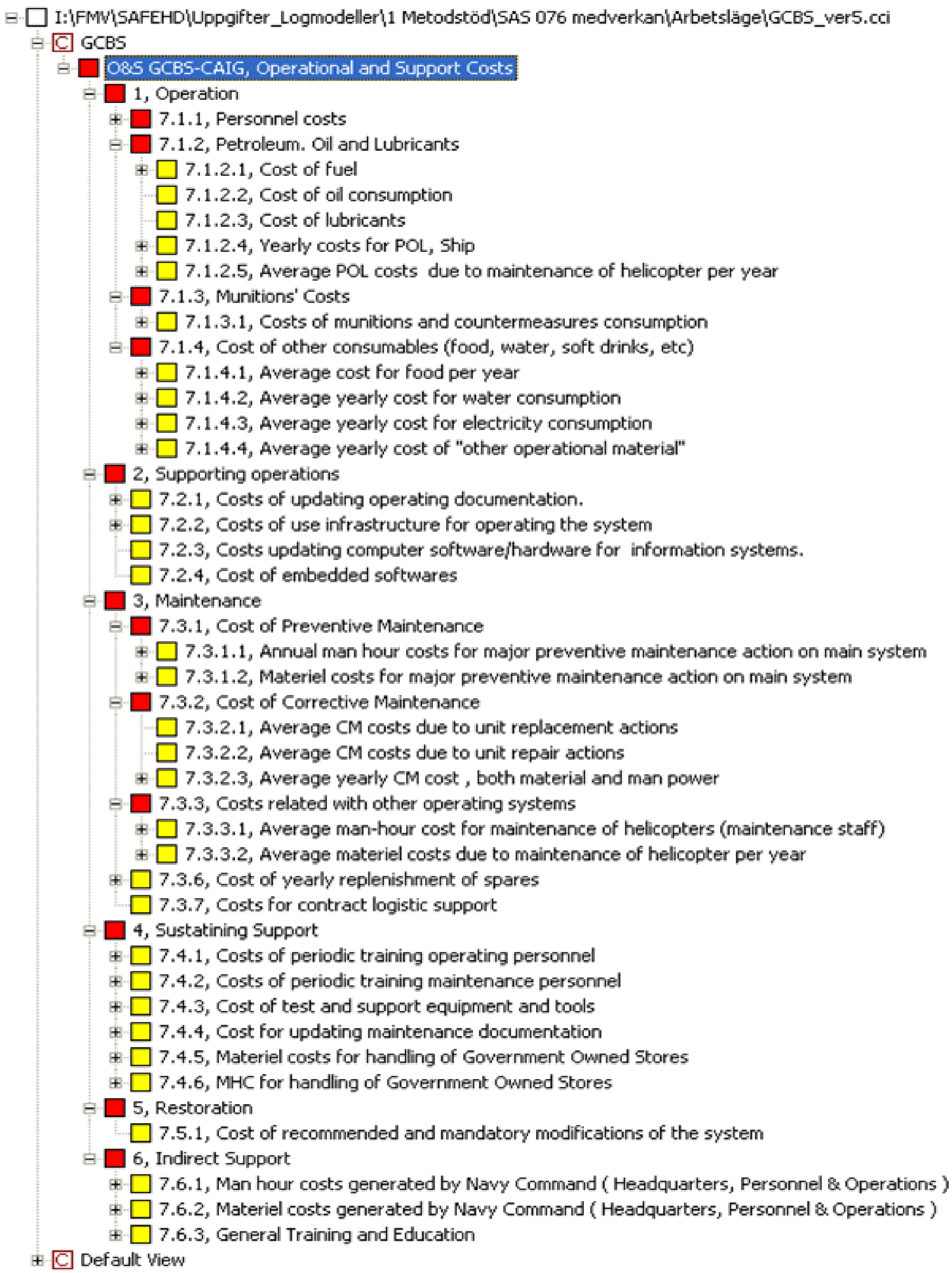

Figure 17: Cost Breakdown Structure for the GCBS-CAIG model

Appendix B2-4: COST BREAKDOWN STRUCTURE FOR THE CAIG MODEL

Figure 18: Cost breakdown structure for the CAIG model

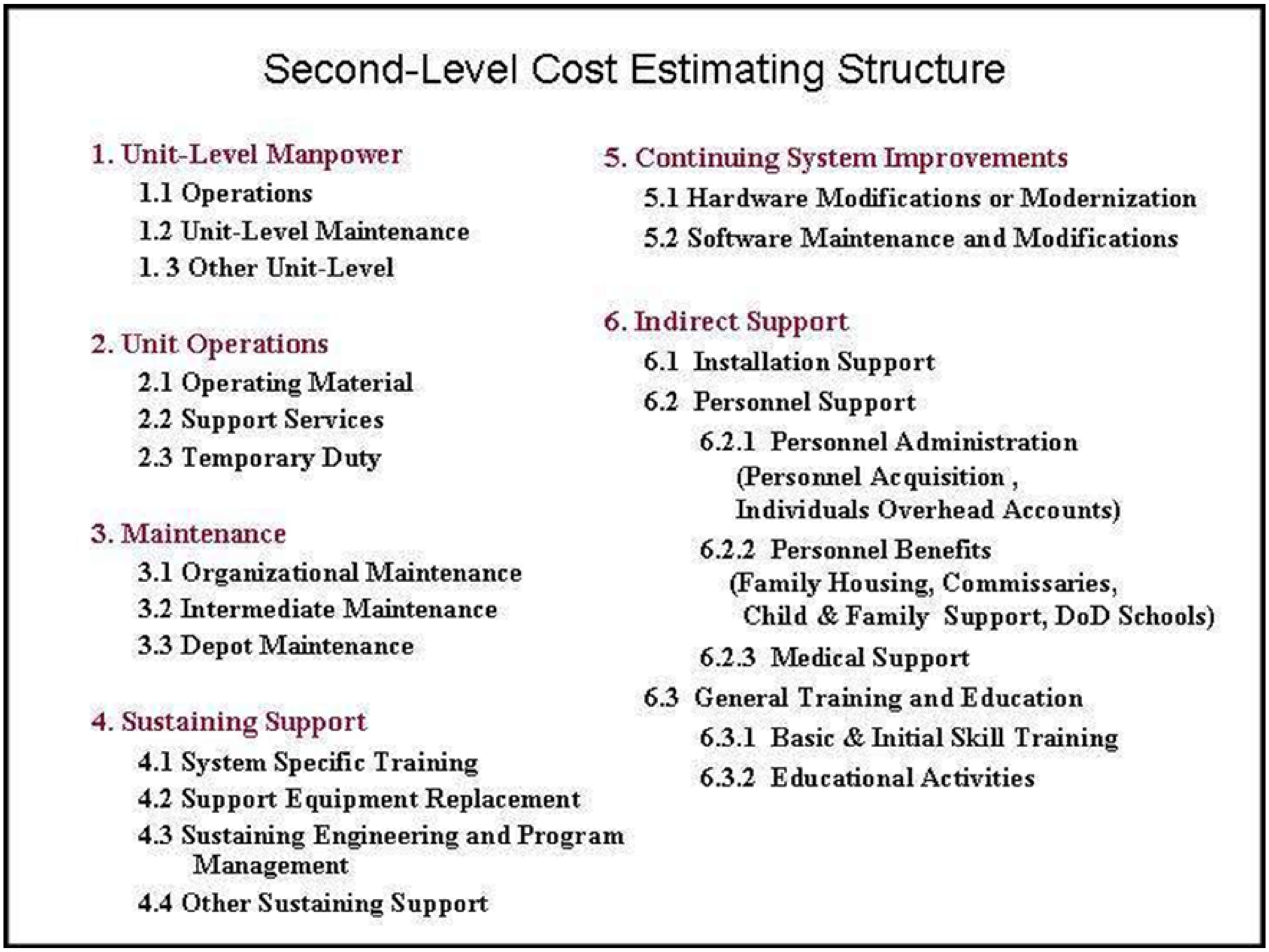

Figure 19: Second-level cost estimating structure

Source: Office of the Secretary of Defense Cost Analysis Improvement Group (CAIG) [8].

Appendix B2-5: TREE REPORT TABLE FOR GCBS-CAIG MODEL

Table 12: Tree Report Table for GCBS-CAIG Model (Cont'd on next page)

Title/Index	Description
1	Operation
7.1.1	Personnel costs
7.1.1.1	Costs of operating personnel
7.1.1.2	Average personnel costs for operation of helicopters
7.1.2	Petroleum. Oil and Lubricants
7.1.2.1	Cost of fuel
7.1.2.2	Cost of oil consumption
7.1.2.3	Cost of lubricants
7.1.2.4	Yearly costs for POL, Ship
7.1.2.5	Average POL costs due to maintenance of helicopter per year
7.1.3	Munitions' Costs
7.1.3.1	Costs of munitions and countermeasures consumption
7.1.4	Cost of other consumables (food, water, soft drinks, etc)
7.1.4.1	Average cost for food per year
7.1.4.2	Average yearly cost for water consumption
7.1.4.3	Average yearly cost for electricity consumption
7.1.4.4	Average yearly cost of "other operational material"
2	Supporting operations
7.2.1	Costs of updating operating documentation.
7.2.2	Costs of use infrastructure for operating the system
7.2.3	Costs updating computer software/hardware for information systems.
7.2.4	Cost of embedded software
3	Maintenance
7.3.1	Cost of Preventive Maintenance
7.3.1.1	Annual man hour costs for major preventive maintenance action on main system
7.3.1.2	Materiel costs for major preventive maintenance action on main system
7.3.2	Cost of Corrective Maintenance
7.3.2.3	Average yearly CM cost , both material and man power
7.3.2.1	Average CM costs due to unit replacement actions
7.3.2.2	Average CM costs due to unit repair actions
7.3.3	Costs related with other operating systems
7.3.3.1	Average man-hour cost for maintenance of helicopters (maintenance staff)
7.3.3.2	Average materiel costs due to maintenance of helicopter per year
7.3.6	Cost of yearly replenishment of spares
7.3.7	Costs for contract logistic support

Table 13: Tree Report Table for GCBS-CAIG Model (Cont'd)

Title/Index	Description
4	Sustaining Support
7.4.1	Costs of periodic training operating personnel
7.4.2	Costs of periodic training maintenance personnel
7.4.3	Cost of test and support equipment and tools
7.4.5	Materiel costs for handling of Government Owned Stores
7.4.6	MHC for handling of Government Owned Stores
7.4.4	Cost for updating maintenance documentation
5	Restoration
7.5.1	Cost of recommended and mandatory modifications of the system
6	Indirect Support
7.6.1	Man hour costs generated by Navy Command (Headquarters, Personnel & Operations)
7.6.2	Materiel costs generated by Navy Command (Headquarters, Personnel & Operations)
7.6.3	General Training and Education

Annex C

The Role of Life Cycle Cost Analysis in Managing the Defense Enterprise

NATO RTO Systems Analysis and Studies Task Group-076*

October 7, 2011

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1.0 INTRODUCTION

1.1 Background

Confronted with expanding and evolving threats to our national security, which range from violent extremist groups equipped with roadside bombs to hostile nations with large standing armies of conscripted soldiers and weapons of mass destruction, the fundamental task of the North Atlantic Treaty Organization (NATO), members states therein, and Partnership for Peace (PfP) nations, in its bare essence, is to manage risk. With limited defense budgets throughout the Alliance, it's impossible for NATO, its members, and its allies to build, equip, maintain and deploy the forces required to meet all of its joint security challenges with perfect and complete confidence. The challenges, such as fighting the long war on terror, protecting our homelands and that of our allies, and preparing to fight and win a large-scale conventional campaign against a near-peer adversary, are simply too onerous. Instead, hard choices must be made amongst competing needs, with risks driven to an acceptable level.

In a national security environment, the business of risk management involves dimensions of difficulty which are often understood with little precision. As Admiral Mullen, Chairman of the United States' Joint Chiefs of Staff, observes "…we live on the cusp of a new era …plagued by uncertainty, change, and unrestricted warfare."[1]. To complicate matters, an entire set of threats to security must be identified and addressed not only today but several decades in advance given the time needed to nurture and harvest promising technologies that could yield a comparative military advantage and to develop, produce, and field major new weapons systems with required capabilities. The Joint Strike Fighter (JSF) aircraft, for example, took roughly ten years to design and develop, and will be in production through roughly 2035, with a service life of decades for each aircraft. By simple arithmetic, then, the JSF will offer a range of capabilities for deterring and defeating threats, but of uncertain and mutable nature, for much of the 21st century.

Threats, of course, can never be anticipated or understood perfectly. Hopefully, they can at least be bounded. John Maynard Keynes, in discussing investment decision of entrepreneurs, noted "…the extreme precariousness of the basis of knowledge on which our estimates of prospective yield have to be made."[2]. This observation on uncertainty often applies as well to assessments of threats, requirements, and capabilities in the national security domain. In defending our nations, however, the loss function for a wrong decision can be infinitely higher than for the private sector. Egregiously bad judgment on Bay Street[1] can lose a company but in national security it can end civilization.

To pile on difficulty, the defense environment is highly dynamic. Our enemies can and do react to any changes in our capabilities, and are quick to exploit weaknesses. This holds at the tactical level, with the evolution of improvised explosive devices in Iraq and Afghanistan but one example, as well as at the strategic, with potential adversaries now seeking to develop anti-satellite capabilities.

1.2 Study Objectives

Given this extraordinarily complex, high-stakes backdrop of strategic planning, capability development, and risk mitigation, the SAS-076 Task Group, under the authority of NATO's Research and Technology Organization, embarked upon an effort to capture national practices in managing the defense enterprise, with an emphasis on the role played by life-cycle cost analysis in the process. These templates were developed to ensure a common denominator of national responses:

[1] Bay Street, Toronto; the "Financial Capital" of Canada

- **Overview**
  Provides an overview of the basic systems or processes used in a nation in managing the defense enterprise;

- **Strategic Framework**
  Captures national practices in defining, managing, and implementing national security strategy;

- **Needs and Solutions**
  Defines the process for identifying military needs and developing and acquiring solutions;

- **Lexicon and Taxonomy**
  Captures national definitions of "defense capability" and defines methods that might be employed in grouping capabilities for the purpose of analysis; and

- **Role of Life-Cycle Cost Analysis**
  Captures the degree to which life-cycle cost analysis plays a role in planning, acquisition, and budgeting.

As a corollary, SAS-076 also examined a pilot effort in capability portfolio analysis (CPA) in the United States which investigated how costs, capabilities, and risks could be examined together in an attempt to engender more informed resource allocation decision making.

In both cases, for the templates and CPA, best practices were indentified by the SAS-076 Task Group. Recommendations are presented herein.

1.3 Scope

SAS-076's expertise lies in the discipline of defense cost analysis. That said, many members of the group have considerable expertise in defense planning. Therefore, within the overall context of managing the defense enterprise, the scope of this effort was limited by a desire to focus on cost-analysis issues.

Although responses from a larger sample of nations would have been desirable, the responses obtained were thought to be sufficient for generating good results, lessons learned, and best practices.

In summary, then, SAS-076 offers no recommendations on critical issues such as strategic planning, capability-based analyses, and on how best to acquire materiel solutions. Instead, the role played by cost analysis in these activities is noted.

2.0 MANAGEMENT OF THE DEFENSE ENTERPRISE

Figure 1 is a useful graphic for describing the management of the defense enterprise [3].

Figure 1: The strategic defense management loop

In NATO and PfP nations, political leaders at the highest level proffer national security guidance or objectives, usually in somewhat lofty, broad terms. Departments and ministries of defense translate this guidance into more concrete policy parameters for building and developing their military forces. In this context, requirements for many countries are defined in term of defense capabilities. This is the "gold standard" in NATO today. Many countries measure performance of acquisition programs, budgets, and military equipment and forces. Fewer, however, seem to measure performance at a strategic level, although the trend is in this direction.

3.0 CAPABILITY PORTFOLIO ANALYSIS

3.1 Background

Many countries within NATO are interested in exploring the methods, processes, and potential benefits of capability portfolio analysis to engender better decisions on the allocation of scarce defense resources. Our first step in SAS-076 was to develop a deeper understanding of the scope and substance of portfolio analysis. As a working hypothesis, we defined this discipline, in a national security context, as the art and science of allocating scarce resources to satisfy strategic requirements.

A literature review revealed that portfolio analysis in the private sector is characterized by

- Uncertain and changing information,
- Multiple goals and strategic considerations,
- Interdependence among projects, and
- Multiple decision-makers and locations [4].

Many of these attributes resonate strongly in the national security arena. Information, especially in wartime, is often uncertain and, at times, tragically unreliable[2]. And the business of defense is certainly dynamic. Threats change and induce changes in requirements and the value of existing defense assets. Further, most of the ships, aircraft, tanks, and helicopters in a nation's arsenal have multiple missions and capabilities, and are highly interdependent with other systems. And there's certainly no shortage of decision makers in a ministry or department of defense, or within NATO HQ.

We also learned that major goals of portfolio analysis typically include

- Maximizing value of individual projects,
- Balancing investments, and
- Adhering to strategy [4].

In the private sector, return on investment for a project is often computed as net present value of future earnings divided by investment dollars. In a defense environment, however, the appropriate computation might be future flows of military capability divided by life-cycle costs, with the numerator a much more amorphous concept than units of money. British defense analysts define military capability as

> "...the enduring ability to generate a desired operational outcome or effect, and is relative to the threat, physical environment, and contributions of coalition partners." [5]

Balance of a portfolio in the private sector is often assessed along the dimensions of research versus production, risk, product categories, and time horizon. These vectors hold in national defense, too. Each ministry of defense needs to balance funding for basic research, acquisition of new equipment, and support and operation of fielded forces. Short-run requirements such as better mine-resistant, ambush-protected vehicles must be balanced against investments in long-term capability, such as Joint Strike Fighter.

[2] See Ambush Alley: The Most Extraordinary Battle of the Iraq War, by British journalist Tim Pritchard, for a heart-rending example. On 23 March 2003 in Iraq, Clausewitz's "fog of war" quickly engulfed the 1st Battalion, 2nd U.S. Marines. Due to an unpredictable sequence of events on the battlefield, which rendered operational plans obsolete, Charlie Company was fired upon by U.S. Air Force A-10 Warthogs who had been mistakenly told there were no friendly forces around the northern bridge in Nasiriyah.

Finally, the Chief Executive Officers (CEOs) of best-practitioning firms want to ensure that projects are selected that adhere to the long-term goals of the company. Indeed, the estimation of a project's value sometimes includes an assessment of its strategic importance [4]. This "on-strategy" objective is equally fitting for defense.

3.2 International CPA Conference

After the literature review, our task group conducted a Capability Portfolio Analysis conference in Paris, France, in an effort to learn more about the application of the discipline in the international defense establishment. We found that many existing models and processes within NATO fall short of the ideal goal of addressing all strategic requirements and the capabilities and costs of all components of the portfolio, large and small alike.

One exception was the Strategy-to-Tasks Model (STAM) of United States Special Operations Command (USSOCOM), headquartered at MacDill Air Force Base in Florida. USSOCOM is the combatant command for the worldwide use of Special Forces such as Navy Seals and Delta Operators[3]. STAM identifies and weighs the importance of strategic requirements and operational and tactical tasks required to meet mission objectives. A board of directors assesses the military value of all assets in the context of these requirements and tasks. STAM does a good job of matching budget to strategy. And it uses impressive methodology in evaluating the warfighting value of assets in the USSOCOM portfolio. However, USSOCOM, unlike most ministries of defense within the Alliance, is not in the business of acquiring multi-billion dollar weapons systems since these are resourced through the Services in the U.S. DoD.

[3] See Inside Delta Force, Delacorte Press, 2002, Erik Haney, for a first-hand description of the skills and valor of 1st Special Forces Operational Detachment - Delta.

4.0 U.S. PILOT EFFORT IN PORTFOLIO ANALYSIS

4.1 Background

Applying theory to practice, the U.S. Department of the Navy (DON) several years ago launched a pilot program for building a construct to actually do capability portfolio analysis [6]. After considerable debate, the CPA team selected the defensive part of mine warfare, or mine countermeasures, as the subject of analysis. The offensive side, the deployment of mines, is of relatively low dollar value. The defensive side, on the other hand, was regarded as small enough to increase the probability of success of the effort yet large enough to maximize lessons learned.

To keep the pilot program within manageable scope, the team decided early on to restrict most of the work to the "materiel" component of the U.S.'s "DOTMLPF" solution space of "doctrine, organization, training, materiel, leadership and education, personnel, and facilities" used in defense planning and execution. Materiel assets are items such as weapons systems, equipment, supplies. For mine countermeasures these includes ships, helicopters, sonars, and marine mammals.

Non-materiel items such as doctrine, of course, can matter greatly, especially in war. Military historian Stephen Ambrose, for example, attributes the stiff resistance of the German army to the Allied invasion of France in 1944 to their superior doctrine and training in fighting in the hedgerows of Normandy[4]. More recently, the success of 2008 surge in Iraq can be attributed not only to an increase in troop strength but also to General Petraeus' doctrine of "securing the population" and, more particularly, to the use of "fusion cells" of intelligence, mapping, and forensic specialists, coupled with Joint Special Operations Command, to locate and target al-Qaeda operatives [8]. In a non-pilot effort, analyses of both materiel and non-materiel alternatives are essential.

In terms of costs, the pilot effort included materiel items and the personnel and training associated with operating and supporting them.

4.2 Mine Warfare

To understand some of the challenges faced by the Navy team in actually doing portfolio analysis, it's worthwhile to briefly describe the fundamentals of mine warfare.

4.2.1 Mission and Threat

The mission of mine warfare is to deploy mines against the enemy and to counter mines that the enemy might deploy against coalition forces.

The threat of enemy sea mines to our maritime forces is pervasive, international, and asymmetric. In addition to terrorist groups, more than 50 countries possess sea mines. They are designed, built, and sold on the international market from friends, second parties, and potential foes alike. Since the end of World War II, more U.S. Navy ships have been damaged or sunk by enemy sea mines than by enemy aircraft and missiles combined.

Adversaries can deploy mines in various depth regimes ranging from deep water to very-shallow water in the littoral, where threat is particularly acute due to the importance of coastal areas in expeditionary warfare and to the enemy's ability to easily, quickly, and cheaply exploit this regime.

[4] Facing an opponent with overwhelming air and materiel superiority, the Wehrmacht nevertheless managed to stymie Operation Overlord for a couple of months [7].

Types of mines include floating, moored, tethered, bottom, buried, rocket-propelled, remotely controlled, metallic, and stealthy.

In 1988, the USS Samuel B. Roberts hit an Iranian M-08 naval mine in the Persian Gulf while escorting Kuwaiti oil tankers during the Iran-Iraq war. The mine's explosion blew a 15-foot hole in the hull and ripped open the ship's engine room. The crew heroically fought flooding and flames and managed to prevent the ship from sinking [9].

She was repaired at Bath Iron Works in Maine at a cost of $90 million to the U.S. Navy. The price of the mine was $1,500.

While the Iranian mine was based on World War II technology, designers and developers of mines continue to take full advantage of commercial advances in electronics, wireless communication, and nanotechnology to make their products more stealthy and lethal than ever.

4.2.2 Portfolio

Figure 2 depicts the threat of sea mines to U.S. naval and coalition maritime forces, and the portfolio of current and planned countermeasures.

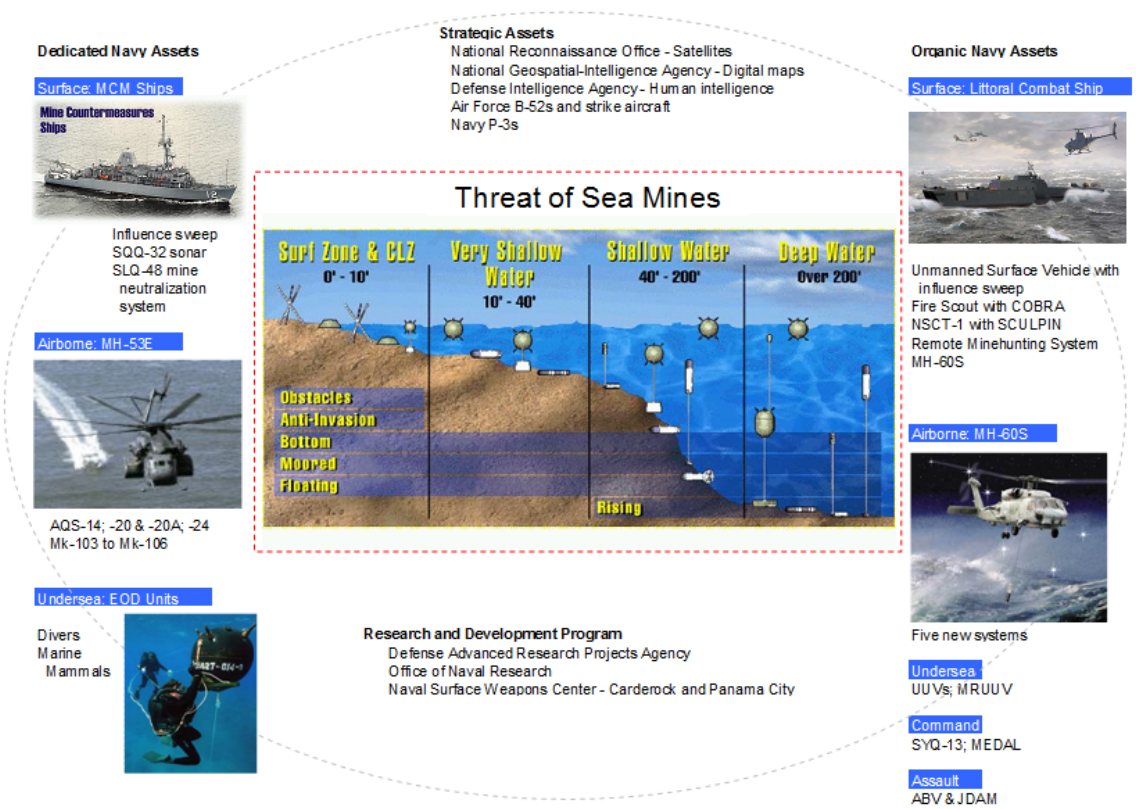


Figure 2: The threat of sea mines

Focusing first on threat, the diversity of depth regimes and the variety of mines within each pose a major challenge to our operating forces, and demand a variety of search and neutralization techniques. In mine warfare, there's no silver bullet or simple solution. One system does not do all. Instead, countering enemy sea mines is regarded as one of the most complex and difficult realms of naval warfare. Multiple systems address the kill-chain steps of *search* (look for objects), *locate* (specify their position in the water, ocean bottom, or beach), *classify* (bin them into mine-like and not-mine-like categories), *identify* (determine which mine-like objects are, in fact, mines), and *neutralize* (render the mines harmless).

Focusing now on counter measures, at the heart of mine warfare is intelligence, surveillance, and reconnaissance. This is where many of our national, strategic assets play a role. These include the National Reconnaissance Office's constellations of polar-orbiting satellites with remote sensing capability; the National Geospatial Intelligence Agency's digital maps of the littoral; and the Defense Intelligence Agency's human, ashore assets which many analysts think will be increasingly important in the decades ahead.

At the operational level, the U.S. Navy uses dedicated and organic assets. The older, traditional dedicated systems are devoted fully or largely to mine warfare. The newer organic assets, on the other hand, travel with Carrier Strike Groups and attempt to meet the Navy's long-standing goal of removing the sailor from the minefield.

Dedicated assets are a triad of surface, airborne, and undersea systems. Included are 14 Avenger-class ships built in the 1980s and early 1990s of fiberglass-sheathed wooden hulls that enable them to operate within minefields. They deploy long cables astern charged with magnetic and acoustical signals that emulate those of our ships and submarines in an attempt to induce enemy sea mines into detonating. The vessels also deploy the tethered SQQ-32 sonar for mine detection and classification and the SLQ-48 for subsequent mine identification and neutralization.

The multi-mission MH-53E helicopter is the largest in DoD's arsenal. The Sea Dragon tows mine-hunting sonar such as the "Q-20" and the newly deployed "Q-20A" to find sea mines and mechanical, magnetic, and acoustic sweep gear to neutralize them.

The Explosive Ordnance Disposal units have the daunting mission of finding and disarming mines. Navy divers work closely with dolphins and sea lions who have a unique ability to find and neutralize mines nestled in the ocean sands.

Turning to the organic domain, the Littoral Combat Ship (LCS), along with its Fire Scout unmanned aerial vehicle[5], will be the U.S. Navy's mine countermeasure platform of the future. The USS Freedom, the first ship in the class, was delivered to the Navy in 2008. The multi-mission vessels will be configurable to perform mine, anti-submarine, and surface warfare missions. LCS will transport manned and unmanned mine countermeasure systems to the littoral, where they will be deployed, while the ship remains offshore and out of harm's way.

The MH-60S Knighthawk helicopter will deploy from the ship, and will carry a number of new mine countermeasure systems which have emerged from the science and technology community and are currently in development or testing.

These include the Airborne Mine Neutralization System and the Rapid Airborne Mine Clearance System which rapidly fires 30mm tungsten projectiles from a Gatling-type gun into the water to destroy enemy sea mines by sheer kinetic force.

Additional assets in the mine warfare portfolio include unmanned, undersea vehicles (UUVs), command and control systems, and assault systems for mine clearance in the surf zone and craft landing zone. Finally, the naval research community continues to develop new technologies for countering enemy sea mines, especially in the littoral.

The U.S. Navy pilot effort excluded the national, strategic assets from consideration. These are classified and devote but a small percentage of their time to mine warfare. This left 46 different systems plus a couple of classes of ships and helicopters to analyze in the portfolio of mine countermeasures.

[5] In its mine countermeasure mode, the Fire Scout will be used for a military task called "intelligence preparation of the battlefield."

4.3 Methodology

4.3.1 Assessing Capability – System Architecture

The naval task group, with strong representation from the mine warfare community, met monthly during much of 2005 to brainstorm ideas for assessing the military value of systems in the portfolio, both current and prospective, and large and small alike[6]. The task group recognized immediately the necessity of tying value to national security goals, set by higher authority. It wanted to avoid the error of operating like loose cannon on the decks of the Department of Defense.

The team received invaluable advice and support from professors and staff at the Naval War College in Newport, Rhode Island, on the business of scoring the importance of objectives. Following the lead of USSOCOM, the team developed a strategy-to-systems model for assessing the military value of systems in the portfolio.

As a backdrop to exercising the model, illustrated in Figure 3, the team first defined a master warfighting scenario. This was an amalgam of two separate scenarios, one for a major combat operation overseas and one for homeland defense, thus giving each of the assets in the mine countermeasure portfolio a chance to demonstrate its true capabilities. While unclassified, the master scenario nevertheless detailed factors such as bottom profile, tactical situation, mine threat, and dimensions and water depth of sea lines of communication.

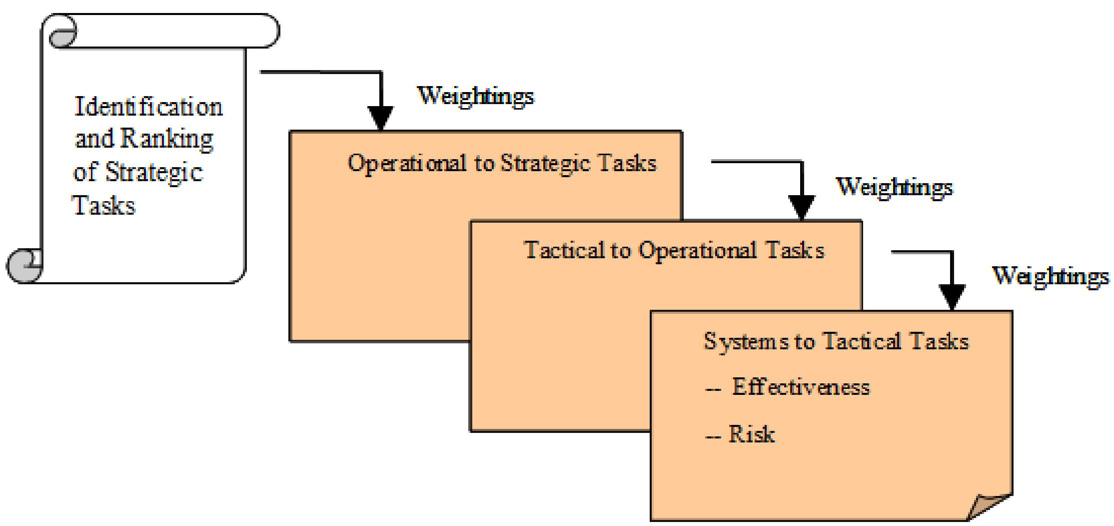


Figure 3: The master warfighting scenario

Next, the team identified and then scored the importance of five strategic tasks or requirements for mine countermeasures. These tasks were tied to National Defense Strategy and recent Presidential directives for increasing security in the maritime domain [10].

The team then defined six operational tasks and scored their importance in fulfilling the five strategic requirements. The team similarly defined 12 tactical tasks and related these to operational tasks. Finally, the team graded individual systems against tactical tasks.

[6]Task group members included representatives from Mine Warfare Command; Naval Surface Warfare Center Panama City; Naval Undersea Warfare Center; Naval War College (Warfare Analysis and Research and the Decision Support Center); Mine Warfare Program Office (PMS-495); the Chief of Naval Operations (Expeditionary Warfare and Mine Warfare); and the Office of Naval Research.

This linkage of strategy to tasks to systems was deliberate. In this sort of schema, those systems that score highest, *ceteris paribus*, are those that best respond to the strategic goals articulated by the President, the Secretary of Defense, and the Joint Chiefs of Staff.

4.3.2 Assessing Capability - Execution Details

The team conducted a scoring conference at the Decision Support Center at the U.S. Naval War College in December 2005. It employed a "Borda Count" technique to measure the rank order and relative importance of the five strategic tasks, shown in Table 1, while recognizing that no flawless procedure exists for doing so. As Arrow's Impossibility Theorem indicates, all techniques to rank-order preferences, other than using a dictator, will violate at least one commonly accepted measure of fairness [11].

Table 1: Scoring of strategic requirements

Strategic Requirements	Sample Score
Protect Operating Forces Against the Threat of Sea Mines for Power Projection Ashore	15
Defend U.S. Ports and Coastal Approaches Against Sea Mines	50
Maintain Mobility of Operational Forces in the Presence of Sea Mines	13
Collect, Analyze, and Share Intelligence Related to the Worldwide Threat of Sea Mines	10
Preserve Freedom of the Seas for Commercial Navigation in the Presence of Sea Mines	12

Each scorer was given a total of 100 points to distribute among the five requirements[7]. While the numbers here are fictitious, "Defend U.S. Ports . . ." did emerge as the top-rated priority in our scoring conference. This is perhaps not surprising upon noting that U.S. ports load and unload from ships an average of 71,000 containers daily [13] and that the value of commerce at the Port of Long Beach alone is $100 billion per year [14].

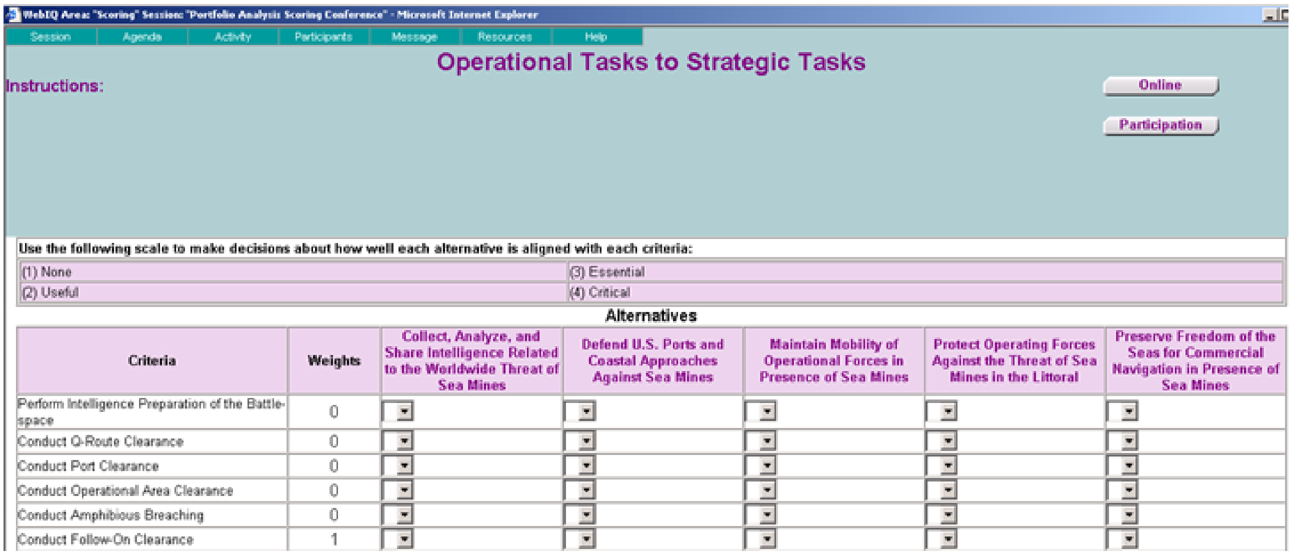
The team scored the importance of each of the six operational tasks in meeting *each* of the five strategic requirements using a template, shown in Figure 4, developed using a web-based decision analysis support tool[8].

After scoring the importance of tactical tasks in fulfilling operational tasks, the grouped the 46 individual mine countermeasure systems into these categories according to their basic function:

- Detection, localization, classification, and identification of sea mines
- Neutralization of sea mines
- Mine sweeping
- Assault

[7] This technique avoids the pitfall of cardinal ordering by measuring the amount by which one requirement is judged more important than another [12].

[8] The six operational tasks and the 12 tactical tasks (not displayed here) were based largely on a distillation of guidance provided in the "Universal Joint Task List" from the Joint Chiefs of Staff and from similar U.S. Navy guidance. The guidance lists military tasks or steps that need to be executed to accomplish a mission, such as countering enemy seas.



WebIQ Area: "Scoring" Session: "Portfolio Analysis Scoring Conference" - Microsoft Internet Explorer

Session | Agenda | Activity | Participants | Message | Resources | Help

Operational Tasks to Strategic Tasks

Instructions:

Online

Participation

Use the following scale to make decisions about how well each alternative is aligned with each criteria:

(1) None	(3) Essential
(2) Useful	(4) Critical

Alternatives

Criteria	Weights	Collect, Analyze, and Share Intelligence Related to the Worldwide Threat of Sea Mines	Defend U.S. Ports and Coastal Approaches Against Sea Mines	Maintain Mobility of Operational Forces in Presence of Sea Mines	Protect Operating Forces Against the Threat of Sea Mines in the Littoral	Preserve Freedom of the Seas for Commercial Navigation in Presence of Sea Mines
Perform Intelligence Preparation of the Battle-space	0					
Conduct Q-Route Clearance	0					
Conduct Port Clearance	0					
Conduct Operational Area Clearance	0					
Conduct Amphibious Breaching	0					
Conduct Follow-On Clearance	1					

Figure 4: Sample scoring template

- Command and control.

The team then rated the *effectiveness* and *suitability* of each system, tackling one category of assets at a time, in executing tactical tasks. This was to keep the scoring manageable and to help insure consistency in evaluating systems with the same mission. *Effectiveness* was evaluated in terms of the overall ability of a system to accomplish its mission. *Suitability* was evaluated in terms of degree of reliability, maintainability, and interoperability of the asset in a warfighting environment.

Aggregate capability scores were tallied for each system using the cascading series of weights from the rankings of strategic, operational, and tactical tasks, applied to the numerical evaluations of effectiveness and suitability. The team converted raw scores into index numbers, using 1.0 as the mean or base value for the entire portfolio.

4.3.3 Estimating Risks

The team assessed risk according to a system's phase in its life cycle:

- **Science and technology projects**
  Risk of failing to meet design, research, and transition goals;

- **Acquisition programs**
  Degree of design, platform integration, and testing challenges;

- **Operational systems**
  Risk of failing to meet mission requirements.

In addition, the team developed risk weighting factors for each phase, running from high to low. An S&T project, for example, carries inherently greater risk than an operational system, *on average*, since it first needs to achieve research goals and then pass through acquisition successfully before becoming a useful military asset. This is not to say that operational systems are without risk. Dolphins and sea lions, for example, are sometimes described as "capricious" in hunting for sea mines. When they want to work, they do a great job. Some days, however, they prefer to play.

4.3.4 Estimating Costs

Measuring military value and risk of 46 systems and four platforms was only half the work of the pilot program. Given the scarcity of resources allocated to national security in a pluralistic, free society, it was essential to scale capability by cost to provide a "value for money" metric, to use a favorite phrase of British defense planners. Team members believed strongly in the criticality of capturing the *total costs* of assets over their *service life* and not simply acquisition costs or costs in the year of the budget[9]. Depending upon where a system was in its life-cycle, this required estimates of development, production, and operating and support costs, as Figure 5 shows.

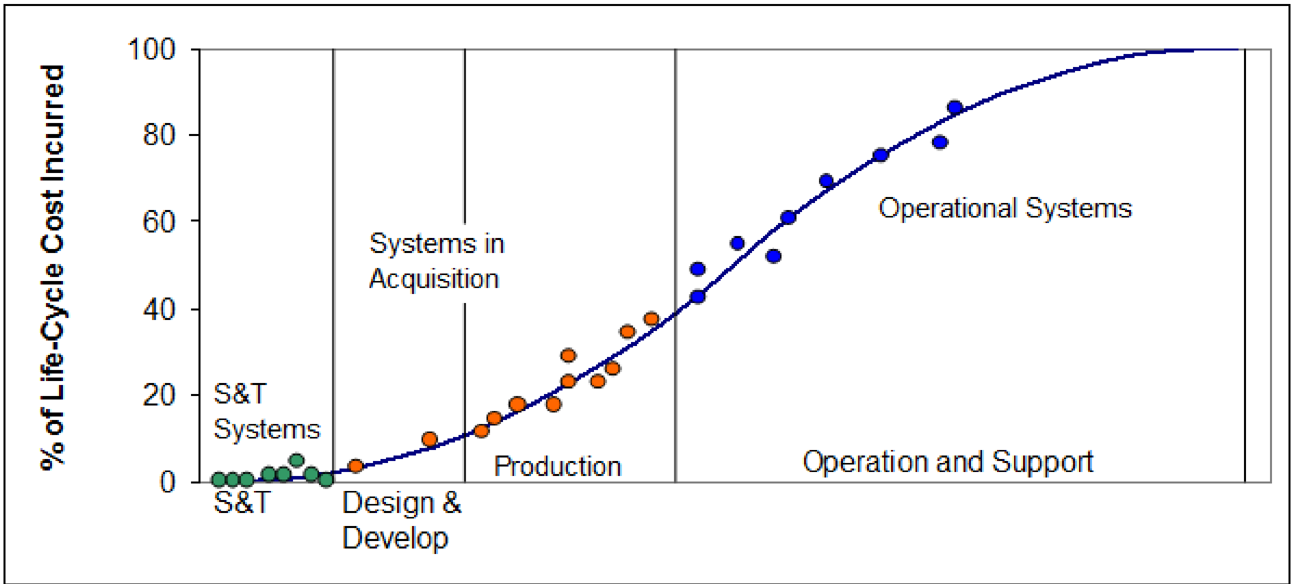


Figure 5: Life cycle of defense systems

The job of cost estimation in the mine countermeasure portfolio was made more difficult because of the numbers of relatively small, inexpensive systems involved. Many of these eluded the minimum dollar threshold for cost reporting in the U.S. DoD, and therefore required a variety of estimation techniques.

4.4 Findings

Combining assessments of military capability and life-cycle cost analysis for the mine countermeasure systems, the naval task group found risk-reward bubble diagrams particularly useful in displaying results. Figure 6 is

[9] In defense cost analysis, operating and support costs are usually estimated for ten years after initial operational capability (IOC) of a system, or the date of fielding. For mine countermeasure systems, this often required estimation of costs through 2020.

an example for the 16 systems in the detect-to-identify-sea-mines category. The size of each bubble represents resources to be expended, or estimated life-cycle costs, in 2006 constant dollars, scaled to a reference point of $100M. Costs include development, production, and operating and support, where applicable. Each accompanying number is an estimated return on investment (ROI), or military value divided by bubble size.

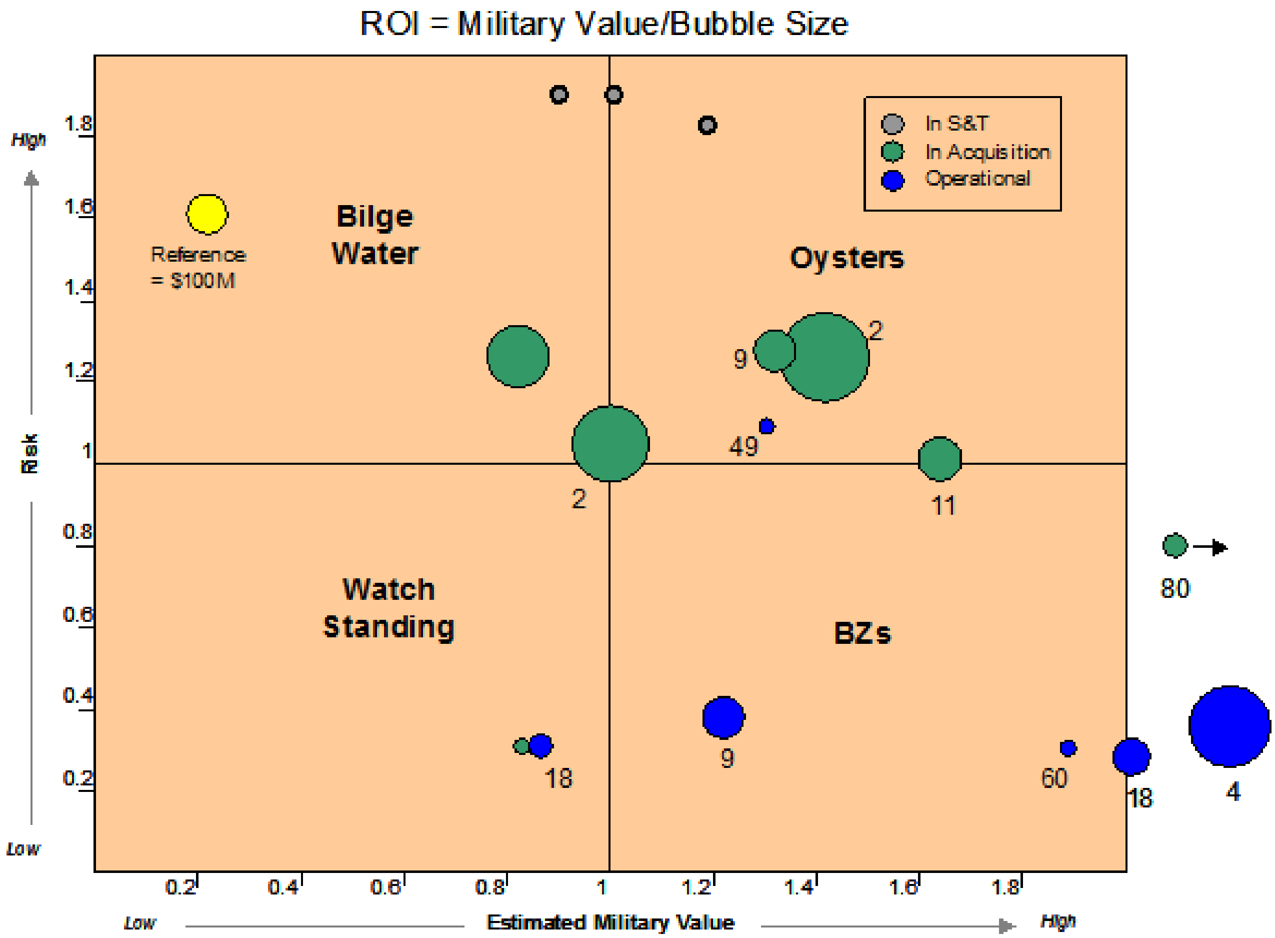


Figure 6: Detection, localization, classification, and identification of sea mines

The two axes intersect at coordinates (1.0, 1.0), the global portfolio average values for risk and reward – measured across all 46 systems.

The team labeled the four quadrants using nautical terminology. The BZs, or Bravo Zulus, meaning "Well Done", are the potential stars, the systems with high return and low risk. Moving in counter-clockwise direction, the Oysters are long-shot programs. These are often projects that could yield a high military return if technological breakthroughs are achieved. Moving along, every organization seems to have its share of bilge water, or at least one project or system of low value that's hard to kill. Finally, the watch standing systems are the no-brainers. These have a high likelihood of success but a low or moderate return. They often involve modifications, extensions, and fixes to older systems.

A couple of observations are readily apparent from the display. First, the detect-to-identify systems do very well as a group. Roughly 2/3 of them fall to the right of the global mean. This is because of the numbers and importance of the tactical, operational, and strategic tasks they support. In mine warfare, it's all-important to find the mines in the first place regardless of mission. U.S. forces sometimes have the opportunity of going over or around sea mines, at least in the short run.

Second, there are profound differences in ROIs. An examination of the underlying data reveals that the deltas are driven mostly by differences in cost rather than effectiveness. The off-the-chart outlier with the ROI of 80, by the way, is a relatively inexpensive unmanned, underwater vehicle designed to engage enemy sea mines in the littoral. Principal decision makers might logically question the acquisition of the more expensive systems. This kind of insight is a potential payoff of portfolio analysis.

Balance in the portfolio can be assessed by evaluating the mix of S&T, acquisition, and operational systems, and their risks and returns, within and between categories of assets. Interestingly, to take one example, S&T projects represent roughly 10% of the total number of systems in the detect-to-identify category but 20% in the mine-sweeping category. But, as Figure 7 shows, sweeping systems perform poorly as a group because of the paucity of tasks they support. Decision makers might logically question if the percentage allocations shouldn't be reversed based on the criterion of relative worth.

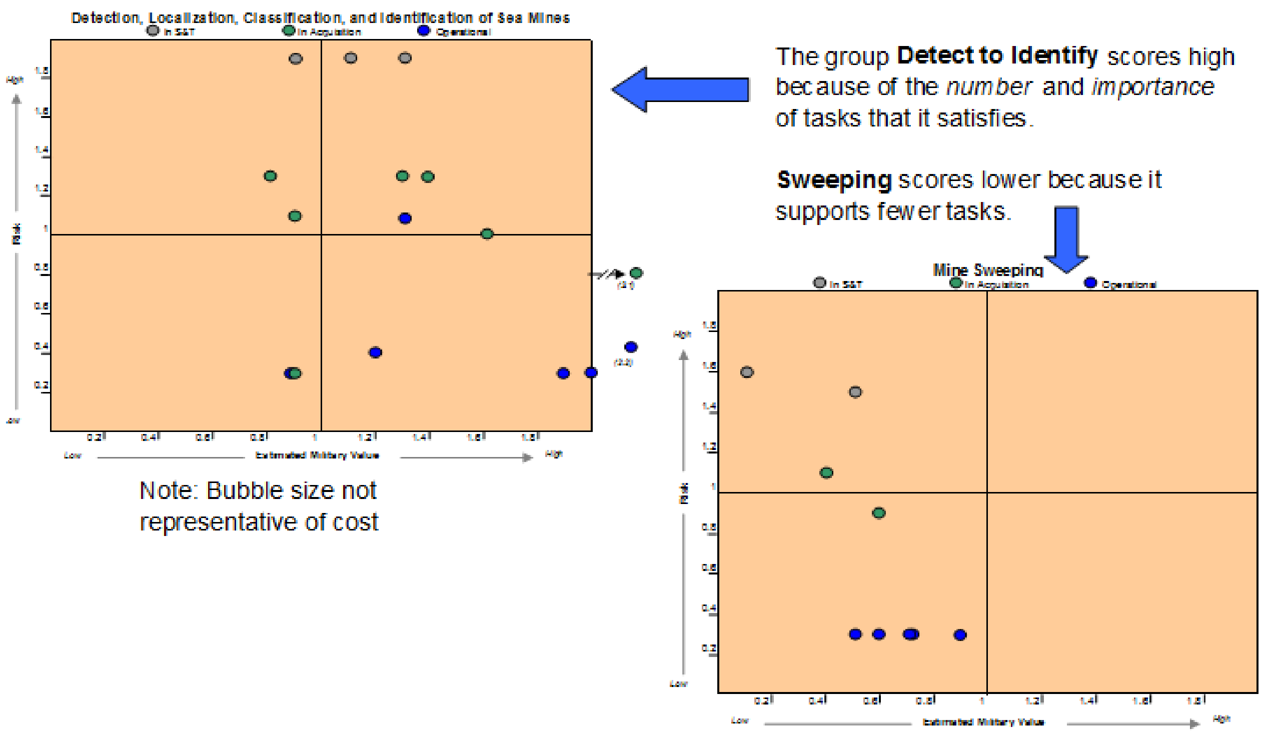


Figure 7: Analysis of detection, localization, classification, and identification of sea mines

Strategic fit is measured implicitly by the numerical military value of a system. The identification and ranking of strategic requirements is the lynchpin of the entire analysis. Weights assigned to strategic requirements cascade to supporting levels of tasks and systems. Any countermeasure asset that doesn't adequately support strategy is simply not going to score well. The lowest-rated system in Figure 7, for example, is an S&T project that appears "off-strategy", at least at first blush. Additional investigation seems warranted into the merits of the project.

In addition to assessing the capability of individual systems, the task group analyzed the military value of groups of interrelated systems. For example, as Figure 8 shows, a number of mine countermeasure systems are deployed from the legacy MH-53E helicopter and from the new MH-60S helicopter, with both labeled “platforms” in the display.

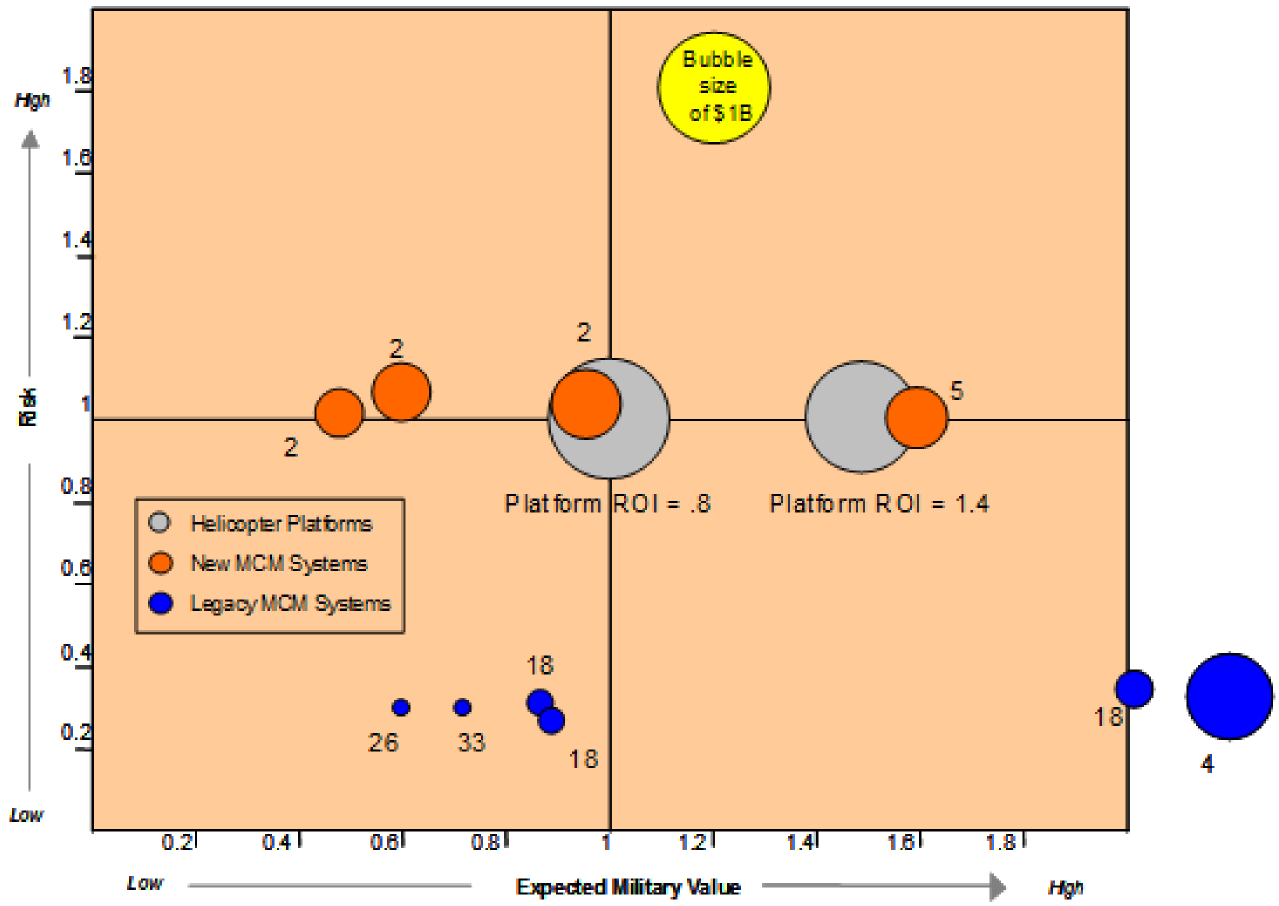


Figure 8: Analysis of groups of interrelated systems: MH-53E and MH-60S helicopters

One helicopter scores higher in capability than the other but their life-cycle costs are roughly the same. The MH-60S is a new system now beginning built. Interesting, its production costs are offset by operating and support costs which are much lower than the expensive-to-operate and aging MH-53E. In terms of the systems deployed from these platforms, the new MCM systems, or those carried by the new helicopter, do not show a marked advantage in capability over the older legacy systems. Indeed, a couple of advanced sonar systems carried by the legacy helicopter yielded the most military value in our pilot analysis.

4.5 SAS-076 Evaluation

The SAS-076 Task Group critically evaluated the U.S. pilot effort in capability portfolio analysis and offers these comments:

- The methodology of the pilot effort seems appropriate for complementing rather than duplicating existing decision-support systems and processes within the ministries of defense in NATO and PfP nations. The pilot's requirements-to-systems model, for example, does not identify capability gaps.
- The pilot effort does not adequately address the dimensions of capacity and time. Identifying the number of units required, for each kind of asset, is critical. Further, some units may be required before others, all have limited service lives, and threats are often highly dynamic and change over time.
- Use of scorers is probably inevitable; however, subjectivity should be minimized and known performance characteristics of equipment better utilized.
- Nevertheless, the pilot effort seems to demonstrate that portfolio analysis techniques can indeed be employed fruitfully in national defense. In short, the pilot effort in mine countermeasures should be regarded as a couple of steps in the right direction in providing senior defense leadership with a tool that measures the costs, capabilities, and risks of individual systems while linking them to national security requirements.

4.6 SAS-076 Recommendations

SAS-076 recognizes that no model is perfect. As the Dutch Econometrician Henri Theil once famously said, "models are to be used, but not believed." [15]. That is, models are parsimonious, plausible, and hopefully informative, but do not provide the ultimate truth. Nevertheless, SAS-076 makes these recommendations regarding future NATO efforts in the area of capability portfolio analysis:

- Include a menu of portfolios from which to choose,
- Include dimensions of capacity and time,
- Include estimates of life-cycle costs,
- Present joint solution space, and
- Minimize subjectivity in assessing military value.

On the first count, the current portfolio or program of record for mine countermeasures was merely one manifestation of reality. Other portfolios are imaginable. "High-tech", for example, would emphasize science and technology projects. A "coalition" portfolio, on the other hand, might include the assets from a NATO Alliance point of view, with many nations having a robust mine countermeasure capability[10]. This addresses another point, or the need to view joint solutions, not only among U.S. DoD components but internationally as well.

On the issue of subjectivity, a key metric in mine warfare is ocean coverage per unit of time. This value is known within fairly tight bounds for many countermeasure systems and can be used in follow-on analysis. However, some use of opinion is inevitable since warfare is both art and science. In short, we need "a nexus of academic rigor and operator experience".

[10] The Netherlands, for example, has a fleet of 10 mine warfare ships [16].

5.0 NATIONAL TEMPLATES

5.1 Overview

Completed templates or presentation slides were received from: Canada, Turkiye, United States, Sweden, Norway, Germany, and the Netherlands. Each, in one fashion or another, attempted to present details on:

- Overview of management of the defense enterprise;
- Strategic framework;
- Needs and solutions;
- Lexicon and taxonomy; and
- Role of life-cycle cost analysis.

5.2 Commonalities and Differences

The SAS-076 Task Group recognizes that every nation within the Alliance, and among PfP nations, has its own procedures and processes for establishing strategic guidance and objectives; for identifying military needs; and for developing and procuring solutions. The application of life-cycle cost analysis, captured in the fifth template, likely therefore differs among nations, too, according to the scope and complexity of its planning and acquisition processes. The SAS-076 Task Group identified the following commonalities and differences in national practices from the nations reporting.

5.3 Strategic Framework

Areas of Analysis

- Goal setting
- Global analysis
- National defense analysis
- Strategy formulation
- Testing the strategy

Summary

All nations in the sample state general goals or ambitions in a national security document. Some nations offer more detail than others. For example, some nations proffer ambitions in a worldwide context while others state goals in the context of specific scenarios. All nations have processes and products that translate high-level objectives into more concrete policy parameters needed to build military forces. Most nations in the sample and many others within NATO engage in capability-based planning.

Legend	
	Yes
	Occasional/Not Concrete
	No
?	Response Unclear

	U.S.	NLD	CAN	SWE	NOR	TUR
Goal Setting						
Stated officially in a document	QDR	Policy View	National Security Strategy	Defense Policy Bill	Defense Policy Targets	Turkish National
Periodicity of publication (x years)	4	4	?	3	?	?
Presented by Ministry of Defense or equivalent	DoD	MoD	MoD	Government	MoD	MoD + General Staff of TAF
Global Analysis						
Described in an offical document		Policy View	National Security Strategy	Defense Policy Bill	?	Turkish National
Periodicity of global anlaysis publication (x years)	4	?	?	3	?	?
Looking ahead (Y) or Static (N)		Scenarios	?		?	?
Period considered for global trends analysis (x years)	20?	?	?		?	?
National Defense Analysis						
Described in an offical document		Policy View	Policy Recommendations	Defense Policy Bill	Strategic Analysis	TAF Operational Requirements
Periodicity of national defense anlaysis publication (x years)	4	4	?	3	3-4	2 (odd years)
Looking ahead (Y) or Static (N)		Scenarios	Policy Options	Mid-term	?	
Period considered for national defense trends analysis (x years)	20	?	?	?	?	2 (even years)
Integration of defense multinational cooperation	?		?	?		
Application of capability portfolio analysis			?	?	?	Occasionally
Strategy Formulation						
Described in an offical document		Defense Plan	First Defense Strategy	Defense Policy Bill	Strategic Defense	Strategy Target Plan
Periodicity of coverage (x years)	20?	10	?	3?	20	10
Describes possible scenarios & reasons for choice of strategy			?	?	?	Occasionally (MODSIM)
Includes considerations on multinational cooperation	?	?	?	?	?	Occasionally
Testing the Strategy	?	?	?	?	?	MODSIM

Figure 9: Summary of analysis of nations' responses with respect to strategic planning.

United States

National Security Strategy, signed by the President of the United States, provides top-level strategic direction and is required by law after a Presidential election. The Quadrennial Defense Review is mandated by law and requires DoD to undertake a comprehensive examination of its strategy and performance.

> *"The Secretary of Defense shall every four years ... conduct a comprehensive examination [the QDR] of the national defense strategy, force structure, force modernization plans, infrastructure, budget plan, and other elements of the defense program and policies of the United States with a view toward determining and expressing defense strategy of the United States and establishing a defense program for the next 20 years. Each such [QDR] shall be conducted in consultation with the Chairman of the Joint Chiefs of Staff."* [United States Code 10].

To date, QDRs have been conducted in 1997, 2001, and 2005, and 2009, and each of those reviews has resulted in substantial changes to defense strategy. The trend has been that the QDR report is the first document that details an incoming Administration's views on national defense, and it generally leads the production of other DoD strategic guidance. National Defense Strategy, signed by the Secretary of Defense, contains guidance on security challenges, key operational capabilities, and operational priorities. National Military Strategy, signed by the Chairman of the Joint Chiefs of Staff (CJCS), provides operational context to the Defense Strategy. Guidance for Employing the Force says how to employ the force in terms of operational plans, global force posture, and aims for security cooperation. Guidance for Developing the Force, on the other hand, contains program guidance; that is, what capabilities should be fielded and when. Both of these documents are supported by more detailed implementing guidance.

Canada

The Government of Canada's national security strategy is typically outlined in several key policy documents, including Speeches from the Throne, major speeches by the Prime Minister, the annual Budget, statements by Ministers in Parliament, and Government announcements. While there is currently no updated overarching national security strategy document, Public Safety Canada (PS) is the federal department responsible for leading the development and implementation of Canada's national security strategy. PS works with five agencies, including the Canada Border Services Agency, the Canadian Security Intelligence Service, and the Royal Canadian Mounted Police, and unites them under a single portfolio and minister. The result is better integration among federal organizations dealing with national security, emergency management, law enforcement, corrections, crime prevention and borders. In addition to coordinating and supporting the efforts of federal organizations to ensure national security, PS also works with other levels of government, first responders, community groups, the private sector and other nations.

A key part of the Government's national security strategy is Canada's defense policy. When a new Government takes office, it will typically set out its defense policy objectives and its corresponding direction to the Department of National Defence and the Canadian Forces (DND/CF). The process for developing defense policy is flexible and varies, but always requires departmental and political involvement.

Canadian defense policy development and planning involves analyzing the national and international strategic environment, the defense and security needs of the country, and the Government's agenda, priorities, and fiscal context. From this, the required military capabilities are identified and policy options are formulated. Working with senior military leadership, the Assistant Deputy Minister (Policy) within DND/CF is responsible for developing policy options, and for coordinating with other departments and agencies (e.g. Department of Foreign Affairs and International Trade; Privy Council Office) to ensure government-wide policy coherence. Consultation with others external to the government may also occur, both with national groups (e.g. Parliamentary committees on defense and security; academia) and international actors (e.g. NATO; partner countries). Once the Deputy Minister and the Chief of the Defence Staff agree on the content of the proposals, policy options are discussed with the Minister of National Defence, who is then responsible for presenting recommendations to Cabinet and the Prime Minister.

The Canada First Defence Strategy sets a detailed road map for the modernization of the Canadian Forces. It puts forward clear roles and missions for the Canadian Forces, outlining a level of ambition that will enable the CF to maintain the ability to deliver excellence at home, be a strong and reliable partner in the defense of North America, and project leadership abroad by making meaningful contributions to operations overseas. Canada First Defence Strategy is the road map for the modernization of the Canadian Forces and is based on analysis of the risks and threats facing Canada in the years to come, as well as the government's vision for defense. The strategic decision-making process for defense acquisitions is called the Force Development (FD) process and the output is the Investment Plan providing detailed guidance on how and when to invest.

The Netherlands

The new Dutch national security planning consists of three new major components in addition to the existing planning mechanisms within the departments:

1. A new government-wide (meta-) foresight function, feeding
2. A national risk assessment which, in turn, forms the basis for

3. A strategic planning system for national security, based on government-wide capabilities-based planning.

Future Policy Survey

In order to develop an adequate conceptual foundation for decisions that will be necessary with respect to the future of the Armed Forces, the Netherlands government initiated the Future Policy Survey. The Survey makes a substantial and scientifically sound contribution to political and public perceptions about the future of the Armed Forces. The Future Policy Survey is an expression of the political will to do justice, now and in the future, to the requirement that the Armed Forces serve as a crucial safeguard against threats to the Netherlands and their society.

The Future Policy Survey project began on 1 March 2008 based on the plan of action approved by the Netherlands defence and on the terms of reference stated in the plan. Its assignment was: "To formulate, on the basis of expected long-term developments and possible scenarios and without constraints, policy options with regard to the future ambitions of the Netherlands defence effort, the appropriate composition and equipment of the armed forces, and the associated level of defence expenditure."(House of Representatives, 2008 31 243, No. 6). The Future Policy Survey makes a scientifically sound contribution to political and public perceptions about the future of the Armed Forces. Among other things The Future Policy Survey has resulted in the development of future scenarios that set out the main outlines of how the world may develop, and the consequences that those developments could bring in the coming two decades. The scenarios have been used as a touchstone for the development of policy options. The policy options have been used to determine the level of Dutch defense efforts over the long term. The results of the Future Policy View have been used as an input for the regular Policy, Planning and Budgeting (BPB–Dutch) procedure. The BPB-procedure contains a policy view and a defense plan. The policy view is the first decision-making document in a 4-year cycle of government and the document determines in outlines the ambition level and the composition and equipment of the armed forces. In the defense plan the policy view is elaborated in more detail and results in the required composition and equipment of the armed forces. The objectives are detailed in activities and required means. The defense plan contains proposals for the design of the organization. The defense plan has a horizon of 10 years, but it includes also topics with a longer timeline.

Norway

The Norwegian Ministry of Defence (NMoD) uses Strategic Defence Reviews (SDR) in the overall planning of the defence sector. In the SDR you conduct a comprehensive examination of the national defence strategy, force structure, infrastructure, budget plan, and other elements of the defence program and policies of Norway with a view toward determining and expressing a defence strategy and establishing a defence program for the next 20 years. SDRs have been conducted on several occasions, the last three in 2000, 2003, and 2007. Norway will continue using SDRs in the future, but will change to a more continuous long-term defense planning process. The scope of most of the studies will be narrower and conducted continuously, with a large review every forth year to sum up the development. Based on the SDR/ decisions in the Parliament, the NMoD develops a Long Term Development Plan (LTDP) where the main goal is to provide strategic guidance and to ensure and maintain a close link between long term planning and the ongoing implementation. Another purpose of the LTDP is to serve as a coherent long-term plan for organization, personnel, material and infrastructure. It gives the NMoD and the Armed Forces multi annual planning guidelines, which again provide a basis for annual planning. The LTDP has four important annexes:

- Structural Development Plan

- Long-term Material Plan
- Long-term Infrastructure Plan
- Long-term Personnel Plan

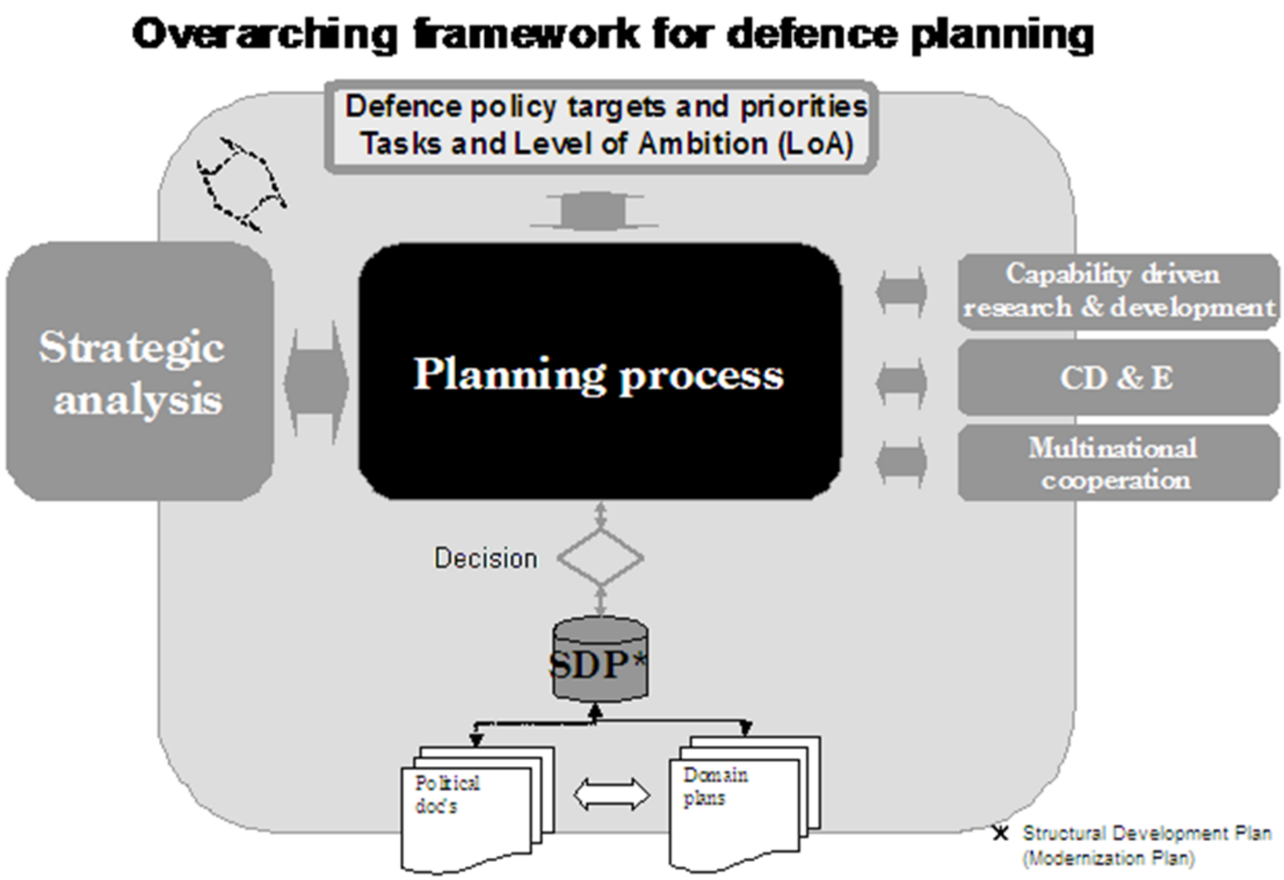


Figure 10: Norway's overall picture of the defence planning.

The model depicted in Figure 10 shows the overall picture of the defence planning and how factors from areas such as strategic analysis, defence policy targets and priorities give inputs and guidance to the planning process. Although it shows a clear distinction between the different areas, the reality is different. It is usually not easy to say where the borderline is between e.g. strategic analysis and the planning process. Furthermore the processes outside the "black box" are just as dependent of the planning process as vice versa.

Sweden

Approximately every third year the Government give directions regarding the Armed Forces in a Defence Policy Bill followed by a Parliamentary Decision. The Defence Policy Bill covers strategic analysis about development in the geographical vicinity, areas of interest for future operations and guidelines for the composition of the units in the Armed Forces. The impact is mainly on the midterm defense planning. Capabilities are not used as a part of the strategic framework. With the same frequency as the Defence Policy Bill the Armed Forces presents the results of the long term planning.

Germany

In accordance with legal provisions, the equipment of the Bundeswehr must be geared towards its mission as defined by political decisions and the tasks derived there from. The economic use of resources demands the exclusive orientation to this mission. In order to be able to accomplish its mission, the Bundeswehr must have certain capabilities. Potential capability gaps—existing or arising—are identified by means of a capability analysis across all organizations and task areas. To close these capability gaps, potential solutions are to be investigated within all planning categories (organization, personnel, armaments, maintenance and operation, as well as infrastructure). Closing a capability gap in the planning category "armaments" (materiel solution) requires activities aimed at determining and meeting the demand. The implementation of these measures must not exceed the scope of resources available within the foreseeable future. Due to its high innovative speed, private industry sets the pace in technological development. Therefore, close cooperation between the Bundeswehr and industry is absolutely necessary in order to be able to maintain modern and efficient armed forces.

Turkiye

Goal settings and global analysis can be found in Turkish National Military Strategy which is signed by President of Republic, Prime Minister, Ministry of National Defense and General Stuff of Turkish Armed Forces (TAF). National Defense Analysis is described in TAF Operational Requirements Plan which is written by military only. This document is updated in every even year. The Strategic Target Plan includes the trends in national defense which sometimes has application of CPA according to technological development in the country and is updated in every odd year. Strategy formulation is defined in The Strategic Target Plan in the next decade with an update in 2 years time. If it includes scenarios which are also tested by MODSIM, 10 Year's Acquisition Plan document is also updated according to the results.

5.4 Needs and Solutions

Areas of analysis

- Needs and solutions
- Use of capability based planning
- Overview of the process
- Years and frequency of coverage
- Use of scenarios
- Responsibility

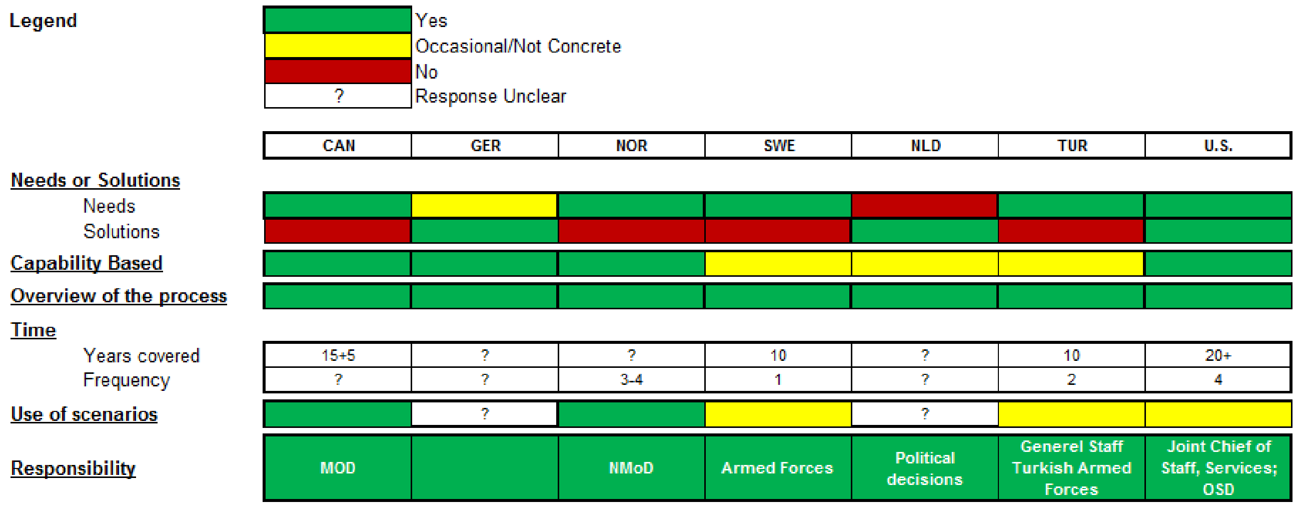


Figure 11: Summary of analysis of nations' responses with respect to defence needs and solutions.

Summary

Most of the sample nations describe their process to identify needs. They all use capabilities as a part of defense planning and execute a gap analysis. All nations seem to have alternative solutions that in different ways are prioritized before any decisions for future acquisition are made. Scenarios are for identifying needs or for describing strategic frameworks or both. This also means that some scenarios are not as detailed as others. The responsibility for working with needs and solutions differs between the nations. This is due to the different governmental organizations in each country.

United States

The U.S. employs a capabilities-based framework called the Joint Capabilities Integration and Development System (JCIDS) for identifying and analyzing needs and the Defense Acquisition System (DAS) for developing and acquiring materiel solutions, with the connection between the two processes shown in Figure 12.

Identification of Military Needs

JCIDS is the process by which DoD identifies, assesses, and prioritizes what capabilities the military requires to fulfill its mission. JCIDS is often referred to as the requirements generation process. The requirements identified through JCIDS can be addressed in a number of ways, including changes in doctrine, training, organization, or the acquisition of a new weapon system.

JCIDS was created in 2003 in an effort to fundamentally change the way the Department develops requirements. Before JCIDS, DoD used a threat-based approach to identify warfighter requirements based on who the adversary might be or where a war might be fought. With the advent of JCIDS, DoD shifted to a capabilities-based approach to identifying warfighter needs based on how an adversary might fight.

JCIDS is overseen by the Joint Requirements Oversight Council (JROC) and supports the Chairman of the Joint Chiefs of Staff, who is responsible for advising the Secretary of Defense on the priorities of military requirements in supporting the national military strategy. Within JCIDS, Functional Capability Boards (FCBs)

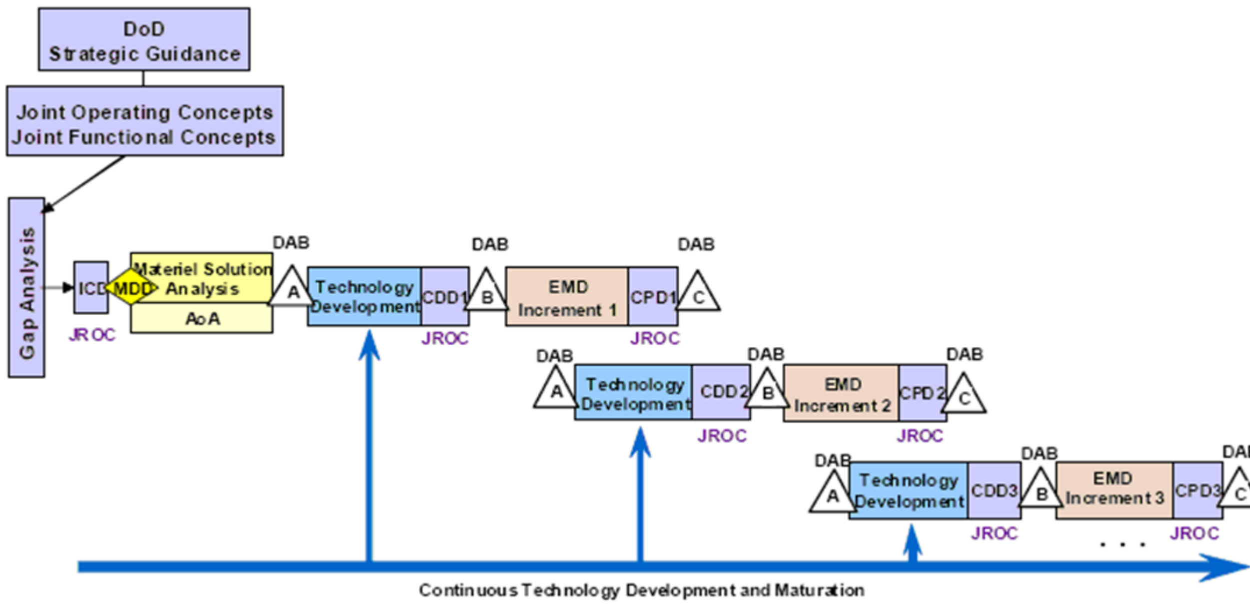


Figure 12: U.S. capabilities-based framework.

manage different capability area portfolios.[11] They are headed by a general or an admiral and made up of military and civilian representatives from the military services, Joint Staff, combatant commands, and the Office of the Secretary of Defense. The FCBs are intended to support the JROC by evaluating capability needs, recommending enhancements to capabilities integration, examining joint priorities, assessing program alternatives, and minimizing duplication of effort across the Department.

The JCIDS process requires the identification of gaps in military capabilities. Potential solutions for filling these gaps are identified and analyzed within DOTMLPF solution space.[12] The results of these analyses or capability-based assessments (CBAs) are formally submitted as initial capabilities documents, or ICDs. An ICD is a capability proposal by a military service, defense agency, combatant command, FCB, or other sponsor. ICDs are intended to document a specific capability gap or set of gaps that exist in joint warfighting functions and propose a prioritized list of various solutions to address the gaps. When a capability proposal is submitted, a Joint Staff "gatekeeper" conducts an initial review to determine what level of joint interest and review there should be and which FCB should take the lead. Capability proposals deemed to have a significant impact on joint warfighting, such as those involving potential major defense acquisition programs, are designated as "JROC interest" and must be validated or approved by the JROC.

The JROC may approve an ICD and recommend a non-materiel solution, such as a change to strategy or tactics. If the JROC approves the pursuit of a materiel solution[13] the program enters the Defense Acquisition System. Documentation developed during the JCIDS process is used throughout the acquisition process.

[11] The JROC charters eight FCBs to perform analyses: Command and Control; Battlespace Awareness; Force Application; Logistics; Protection; Force Support; Net Centric; and Building Partnerships.

[12] Doctrine, organization, training, materiel, leadership and education, personnel and facilities.

[13] A materiel solution is any item (including ships, tanks, self-propelled weapons, aircraft, etc., and related spares, repair parts, and support equipment, but excluding real property, installations, and utilities) necessary to equip, operate, maintain, and support military activities without distinction as to its application for administrative or combat purposes.

Development and Procurement of Materiel Solution

DoD purchases goods and services from contractors to develop and maintain the force, including related infrastructure. Any purchase of a good or service by DoD is defined as a procurement. In contrast, the term defense acquisition is a broader term that applies to more than just the purchase, or procurement, of an item or service. The acquisition process encompasses the design, engineering, construction, testing, deployment, sustainment, and disposal of weapons or related items. More formally, the Defense Acquisition System for designing and acquiring materiel solutions is

> "... *the management process by which the Department of Defense provides effective, affordable, and timely systems to the users, [and it] exists to manage the nationÕs investments in technologies, programs, and product support necessary to achieve the National Security Strategy and support the United States Armed Forces.*"

As depicted in Figure 13, the Defense Acquisition System uses "milestones" to oversee and mange acquisition programs. Each milestone has specific requirements. A program must meet these requirements (statutory and regulatory) in order to proceed to the next phase in the acquisition process. The Milestone Decision Authority (MDA) is responsible for deciding whether a program meets the milestone criteria. Depending on the program, the MDA can be the Office of the Undersecretary of Defense (Acquisition, Technology, & Logistics) or an acquisition executive in a DoD component, such as a Military Department.

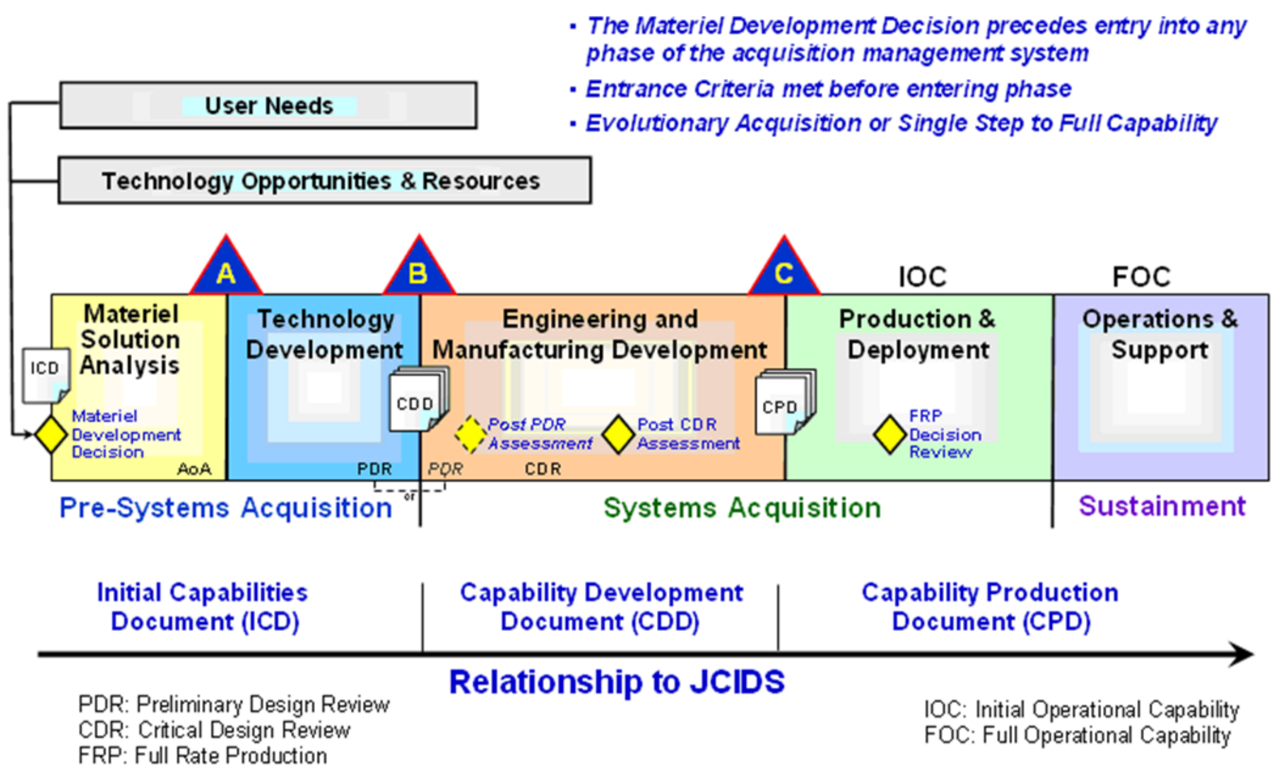


Figure 13: U.S. defense acquisition system milestones.

To enter the Defense Acquisition System, a program must pass a Materiel Development Decision (MDD) review, chaired by a Milestone Decision Authority. At the review, JROC recommendations are presented by the Joint Staff, and the relevant component presents the Initial Capabilities Document, which details the operational need for a materiel solution. During the Materiel Solution Analysis phase, an Analysis of Alternatives (AoA) is conducted and a Technology Development Strategy (TDS) is created. The Technology and Development phase is where a program determines what technologies are required to develop a materiel solution, and works to mature those technologies. This phase is also where competitive prototyping occurs. The Engineering and Manufacturing Development phase is where a system (or increment) is developed, full system integration occurs, and preparations are made for manufacturing, including developing manufacturing processes, designing for producibility, and managing cost. The Production and Deployment phase is where a system is produced and deployed. At Milestone C, the MDA authorizes the beginning of low-rate initial production (LRIP), which is intended to both prepare manufacturing and quality control processes for a higher rate of production and provide production representative articles for operational test and evaluation (OT&E). Upon completion of OT&E and demonstration of adequate control over manufacturing processes, and with the approval of the MDA, a program can go into full rate production. When enough systems are delivered and other pre-defined criteria are met, an Initial Operating Capability (IOC) can be attained, allowing for some degree of operations. Full Operational Capability (FOC) is achieved when the system is ready to operate as required. After development and production, a system enters the sustainment phase. Finally, programs are divided into acquisition categories (ACATs) based primarily on program value. Management and oversight of acquisition programs increases as the value of the program increases. The most significant DoD and Congressional oversight activities apply to major defense acquisition programs (MDAPs), which are categorized as ACAT Is.

Canada

Canada, in their template, has described a process focusing on needs, not how to develop solutions. The process is capability based. The strategic decision-making process for defense acquisitions is called the Force Development (FD) process and the output is the Investment Plan. The Investment Plan covers 15 years with the first 5 years in detail. The plan provides a rationale for new projects and funding provision of them.

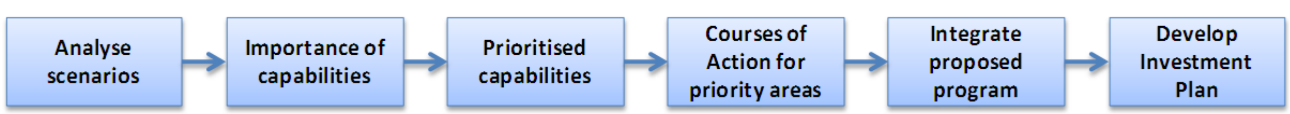


Figure 14: SAS-076's interpretation of Canada's force development process.

The process starts with development and analysis of scenarios that are representative for future missions. Starting with the scenarios it is possible to determine the relative importance of different capabilities and prioritize the capabilities for investment, sustainment or divestment. Courses of action for priority areas and selected preferred options are developed and proposed program changes are integrated with existing programs. Finally an integrated Departmental resource plan (Investment Plan) is developed. Multiple planning scenarios are used to determine likelihood of use and criticality of delivery of different capabilities. Environmental Chiefs of Staff, Chief of Force Development and Chief of Program work within the process.

The Netherlands

The Netherlands, in their template, has described a process focusing on solutions, not how to develop needs. Capabilities seem to be a part of the process although it is not described in what way they are used. The process used to identify and acquire the different solutions, i.e. different materiel, is called Defence Material Process (DMP). The DMP is divided into several phases: each phase is ended with a DMP-document.

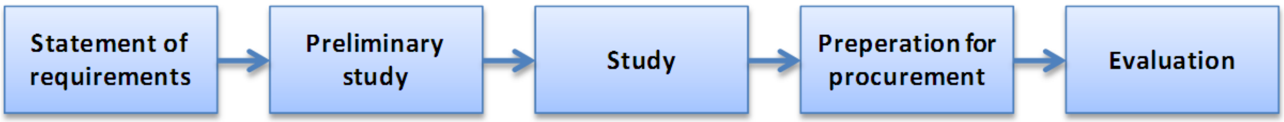


Figure 15: SAS-076's interpretation of Netherlands' defence material process.

DMP is the guideline for keeping the materiel management process on track and contains rules for realizing the requirement for materiel procurement. Financial claims are described. The preliminary study results in an initial selection of product alternatives, including a short list of most suitable alternatives. The Study phase should result in a validation or reassessment of qualitative & quantitative requirements, the detailed requirements and norms the product must comply with and used to compare and evaluate alternatives; an estimate of the life-cycle costs of each alternative product and the financial implications of the alternatives and, if necessary in a development process or a prototype trial, the outcome of the tenders. Preparation for procurement results in a choice of a particular product and the work includes validation or reassessment of requirements, results of development, specification of estimated project expenditure resulting, etc. The final phase, Evaluation, applies for projects exceeding Euro 250 million and is applied when a system has been in use for some time. The parliament is informed of the evaluation. The DMP provides for political decision making at important milestones and political and non-political steering throughout duration of project.

Norway

Norway, in their template, has described a process focusing on needs, not how to develop solutions. The process to identify military needs is capability based and called Capability Planning. The process maintains a link between defense- and security policy foundation, defense tasks and level of ambition, and main decisions concerning development of capabilities and how Defense Forces are structured. The Capability Planning starts with Task analysis related to tasks stated in parliamentary bill. A complete list of capabilities needed to solve imposed tasks is developed and then the level of ambition is stated. The Gap analysis identifies and analyzes the gap between the ability the structure has today and the defined capability need. A prioritizing is made based on probability, impact and economy. Finally the capability development plan is developed. The plan describes the gaps that are prioritized and in what way they will be closed.

Figure 16: SAS-076's interpretation of Norway's capability planning process.

The Capability Development Plan is used to adjust the Structural Development Plan which is part of the Long Term Development Plan (LTDP). LTDP is a result of Strategic Defense Reviews which historically have been made every third or fourth year. Besides Capability Planning there is Structural Planning to maintain development of Defense Forces within defined lines of development and capability requirements and acquire capabilities through decisions on structural development and planned allocation of resources. Use of scenarios is not specified although they are used and their role in defense planning has been described earlier (example: conference in Paris). NMoD is responsible for the work with support from the Norwegian Defense Research Establishment (NDRE).

Sweden

Sweden, in their template, has described a process focusing on needs, not how to develop solutions. It is not explicit in the answer but capabilities are a part in the defense planning. But capabilities are not the only way to identify needs and a more capability based approach is discussed.

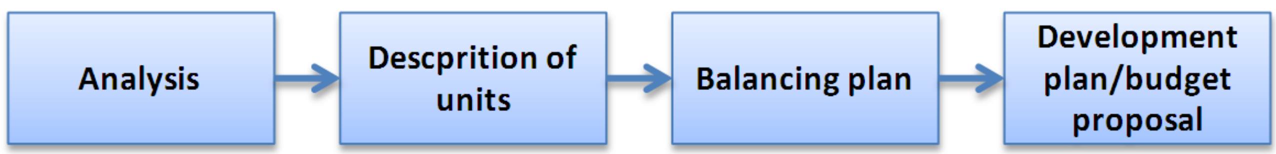


Figure 17: SAS-076's interpretation of Sweden's defence planning process.

The defence planning process starts with an analysis in order to describe the difference between the current plan and future needs. The difference between the plan and the identified future needs is the basis for the changes that needs to be done within the military units. The units are described considering for example number, quality and costs related to personnel, acquisition and exercises etc. All changes are prioritised. The development plan and the budget proposal must be funded, this is done by balancing the plan. When the plan is balanced it is possible to put together the development plan and the budget proposal. The development plan contains information about the number of military units, acquisition of new systems, a plan for ongoing and coming operations, and so on. The acquisition planning cycle starts from decisions taken in the development plan. The midterm defence planning covers the time frame up to ten years and it is normally revised once a year. The result of the defence planning is the Armed Forces' development plan and a budget proposal. The development plan describes in detail the Armed Forces for the first three years in the period and work as a guideline for the remaining years. Scenarios are used to prioritize capabilities. The Armed Forces are responsible for the process.

Germany

The information regarding the German process describes both needs and solutions but is focused on the solutions. The process is capability based. Potential capability gaps are identified by capability analysis across organizations and tasks. Potential solutions to close capability gaps can be identified not only by acquisition of new material but with a changed organization, infrastructure etc. Implementation of solutions must not exceed the scope of resources available. Customer Product Management (CPM) is the process used to determination and meeting the capabilities needed. The process is determined by principles of cost-effectiveness.

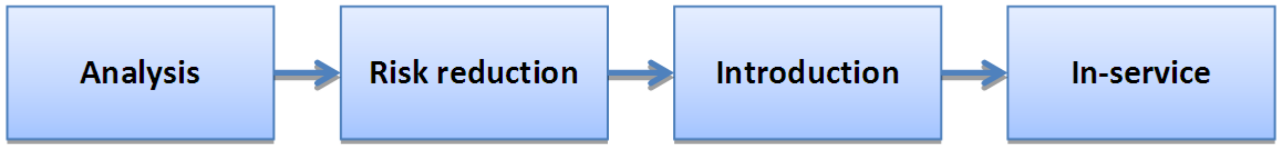


Figure 18: SAS-076's interpretation of Germany's customer product management process.

Determination and meeting of demands is divided into the phases analysis, risk reduction, introduction and in-service phase. During the analysis phase, the demand is determined and information to be able to select and implement the selected solution is gathered. Risk reduction means that all necessary steps is taken to ensure that risks relating to performance, time and cost aspects are reduced. During the introduction phase, development work will be rendered as part of a purchase—or manufacture- (construction-)—based contract and serves the purpose of adapting the solution to the requirements and preparing it for production. Development activities during the in-service phase serve to maintain initial operational capability. The Bundeswehr Chief of Staff determines required Bundeswehr capabilities, the Director General of Armaments and the IT Director are involved in the performance of the technical and economic assessment. The Chiefs of Staff of the armed services, the MOD Directors and the IT Director participate in the capability analysis. The Director General of Armaments, the IT Director and the Director of Defense Administration each assume ministerial responsibility for the provision of the appropriate products and services required to close capability gaps within their respective areas of responsibility.

Turkiye

"Scientific Decision Support" methods are used in the planning activities process in the fields of operations, force, personnel, logistics, intelligence and health as well as in the planning and programming of the capabilities and systems that the Armed Forces must have to ensure the defense and survivability of our country according to the current and future requirements. The process regarding the above-mentioned scientific decision support methods is basically composed of the following stages:

- Definition of the need for analysis/question,
- Collection and compilation of the required data,
- Making analyses through analytical models and simulation systems,
- Generation of decision alternatives and their presentation to the decision-making authority.

The outputs of needs & solutions analysis which is done by "Scientific Decision Support" are mentioned in "Strategic Target Plan" as the needs required and "10 Years' Acquisition Plan" as the solutions. Both documents cover next ten years with updates in each 2-year period and the responsibility of these documents is given to General Stuff of TAF.

5.5 Lexicon and Taxonomy

Most nations from the sample seem to define capability in terms of ability to achieve a desired outcome. Regarding components of the capabilities there seems to be a significant commonality. The result of the template shows that some nations use a much more extensive structure than others.

- Definition of a defense capability: Most nations seem to define capability in terms of ability to achieve a desired outcome.

  - **Turkiye:** Activities process in the fields of operations, force, personnel, logistics, intelligence and health as well as in the planning and programming of the capabilities and systems that the Armed Forces must have to ensure the defense and survivability of our country according to the current and future requirements.
  - **United Kingdom:** The enduring ability to generate a desired operational outcome or effect, and is relative to the threat, physical environment, and contributions of coalition partners.
  - **United States:** The ability to achieve a desired effect under specified standards and conditions through combinations of means and ways to execute a specified course of action.
  - **Canada:** Identical to definition used by the U.S.
  - **Norway:** The ability to complete a given task.
  - **Sweden:** Activities for which units have been acquisitioned and trained to reach a specific effect depending on scenario and ambition.
  - **The Netherlands:** The only definition used by The Netherlands relates to capability, and is taken from the NATO Bi-SC (Strategic Command) Agreed Capability Codes and Capability Statements dated 16 April 2008. It reflects operational capabilities which the armed forces, or a part thereof, should or can have.

- Components of capability: There seems to be significant commonality as shown here:

  - **Turkiye:** Doctrine, Training, Education, Leadership, Organization, Materiel, Personnel
  - **Canada:** Personnel, Research and Development, Infrastructure, Concepts and Doctrine, Information, and Equipment (PRICIE)
  - **United States:** Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities (DOTMLPF)
  - **Norway:** Protection, Means of Action, ISTAR, C2, Mobility, Support
  - **Sweden:** There is no stipulated list of components of the capabilities. However they can be described in terms of *Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities* or other similar expressions.
  - **The Netherlands:** DCTOMP(F): Doctrine, Command, Training & Education, Organisation, Materiel, Personnel and Finance

- Taxonomy: Some nations use a much more extensive structure than others.

- **United States:** Like capabilities are functionally grouped into Joint Capability Areas (JCAs) which cover 100% of DoD's budget and warfighting capability. Tier 1 JCAs are broken down into increasingly finer degrees of detail. Eventually, specific capabilities are linked to discrete warfighting tasks, such as neutralizing enemy sea mines in Very Shallow Water. Capabilities and associated tasks number in the thousands.
- **Canada:** The Canadian Capability Framework comprises five capability domains: Act, Shield, Sustain, Command and Sense. These are each expressed as a hierarchical tree of capabilities that cover all of the operational outputs of the Canadian Forces. The five domains break down to 336 discrete capabilities. A sixth domain, Generate, is identified as covering all of the non-operational capabilities of the Department of National Defense and the Canadian Forces (DND/CF), but has not yet been further developed.
- **Norway:** Broad capabilities are defined for each of the six major domains. Examples are Protection-Land-Heavy Machine Gun and Support-Joint-Medical Services.
- **Sweden:** The Swedish Armed Forces uses a model with Core Tasks, Defence Tasks and Defence Capabilities. The different tasks and capabilities are used to help the organisation to describe mission of the Armed Forces. An example of a Core Task is protecting the integrity of national territory, an example of a Defence Task is guarding maritime territory and finally an example of a Defence Capability is effect on sea targets. There are approximately 80 capabilities.

5.6 Role of Life-Cycle Cost Analysis in Defence Planning

Areas of analysis

The responses of each of the nations were analyzed with respect to the role of life-cycle cost analysis during three phases of defence planning and acquisition:

- Identification of needs;
- Programming and budgeting; and,
- Acquisition of materiel solutions.

For each of these phases, SAS-076 analyzed the nation's response in terms of:

- Requirement for LCC analysis;
- Performance of LCC analysis; and,
- Guidelines for LCC analysis.

Furthermore, when it was determined that LCC analysis is performed, SAS-076 analyzed whether the results of the LCC analysis were used by the nation for:

- Economic information;

- Prioritization;
- Affordability assessment; or,
- Analysis of alternatives.

Summary

Of the seven nations answering the template only one nation uses life-cycle costing both for identifying defense needs, for defense programming and budgeting and for acquisition of materiel solutions. The best commonality is identified in the field of acquisition of materiel solutions.

Figures 19 and 20 provide a high-level summary of the SAS-076 analysis. As indicated by the legend in Figure 19, colours are used to evaluate the degree of use and role played played by life-cycle cost analysis during the various stages of defence planning and acquisition. Green indicates that life-cycle cost analysis is usually performed and plays a role in decision making. Red indicates the opposite—life-cycle costing does not play a role. Yellow indicates that the use of life-cycle costing is occasional or the that the nation's response was not concrete. Question mark entries ("?") indicate that the nation's response was unclear or did not provide enough information to evaluate. Figure 20 illustrates the micro analysis which is then combined to obtain Figure 19.

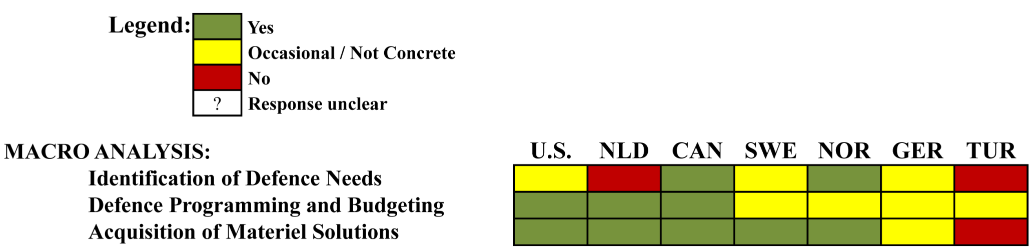


Figure 19: Macro analysis of role of life-cycle cost analysis in defence planning.

United States

The center of gravity of life-cycle cost analysis in the U.S. is in support of acquisition of materiel solutions. Little or no support is provided for strategic planning and only ad hoc support during the identification of defence needs. Guidance for this latter phase merely recommends the execution of affordability assessments. Life-cycle cost analysis supports budgeting more than programming. Due to recent statutory requirements, the U.S. defence budget now needs to reflect the acquisition cost estimates from each of the services. The acquisition of materiel solutions is heavily and extensively supported and informed by cost analyses which are required at milestones A,B,C, and full-rate production decision reviews. Over 1,000 government, in-house cost analysts provide this support.

Norway

Norway, one of the very few countries in the world with a national monetary surplus or negative national debt, sets the standard within NATO for use of life-cycle cost analysis early in the strategic planning process (identification of defence needs). This Norwegian penchant for sound fiscal constraint and avoidance of budget

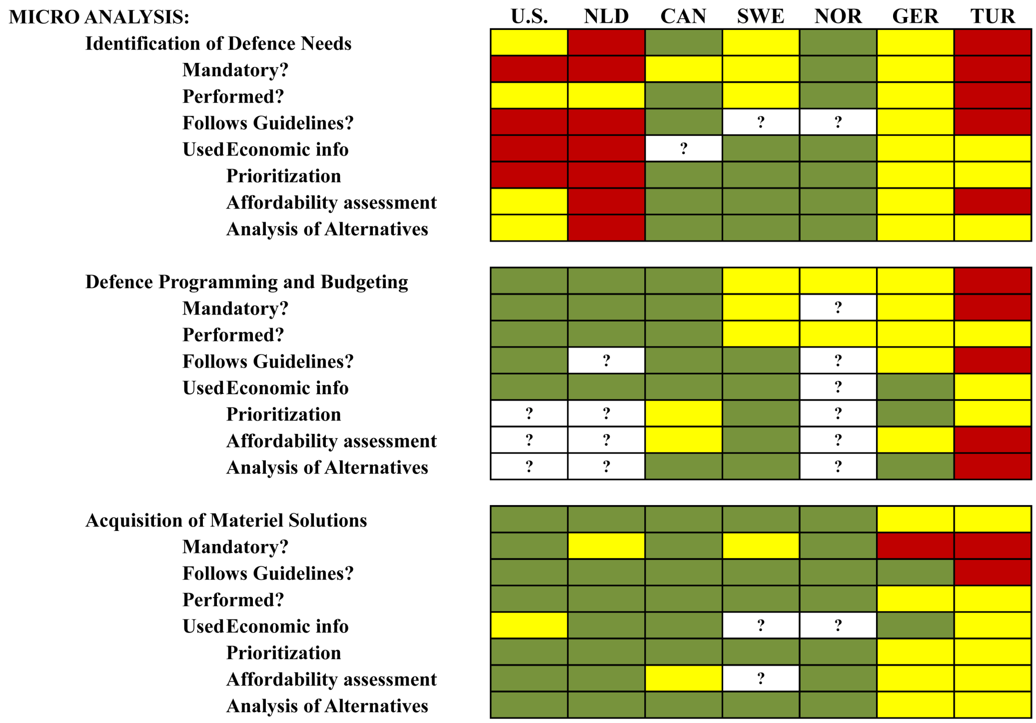


Figure 20: Micro analysis of role of life-cycle cost analysis in defence planning.

deficits helps ensure that national will matches national wallet. Norway believes that it's all-important to get the costs right the first time and simply not to develop, build, and deploy systems that are unaffordable. Along these same lines, life-cycle costs analysis extensively supports the acquisition of materiel solutions, either new developments or COTS procurements. Costs and capability tradeoffs are considered, as well as operating and support costs during the in-service phase of a program's life cycle.

Sweden

In Sweden, force-structure cost analyses is conducted during the long term strategic planning process. To direct the force structure planning process, the Swedish Ministry of Defence can give indicative levels for total future expenditures. The Swedish defence planning process analyzes the difference between the current and future needs. The difference between the two provides the basis for changes and the expenditures that these changes will induce are estimated. The sum of all suggested changes are then balanced against each other in the exercise called balancing the plan resulting in a new development plan. All changes are prioritised so it is possible to choose which changes to start with if there is not enough budget to do them all. There is an equipment acquisition strategy which stipulates that the equipment acquisition should be cost efficient from a LCC-perspective, and there is a directive stipulating how the LCC-estimates should be prepared.

The greatest percentage of resources in the cost community is devoted to support the defense acquisition system, but there are no mandatory directives in the field of cost estimation and analysis, only advisory and instructional policies. Further cost analysis support is provided for development and optimization of support systems, of the systems maintainability and reliability, of contractor source selection and earned value management.

The Netherlands

Netherlands is perhaps the only country in NATO that takes a "whole of government" (WoG) approach to national security planning. Strategic requirements and identification of needs and solutions cover the entire spectrum of national defence and civil concerns. Like the U.S., defence cost analysis supports acquisition of materiel solutions very extensively. This often involves make-or-buy decisions for weapon systems based on their estimated life-cycle costs. Furthermore cost and capability tradeoffs are commonplace. In the earlier stages of national planning, cost analysis employed far less frequently. For example, elements of risk (e.g., breach of dyke system or occurrence of a pandemic virus) are analyzed in terms of probability of occurrence and consequence. Cost, however, is not a dimension of the analysis at this early stage of planning.

Canada

As part of Canada's capability-based planning process, life-cycle costs are taken into consideration during the identification of defence needs phase of defence planning. At this early stage cost estimates rough order of magnitude calculations based on PRICIE cost breakdown models are employed. During the programming and budgeting phase—Canada's integration phase of its capability-base planning process—these rough order magnitude costs are considered during the decision process and used for prioritization of alternatives and further economic planning. Prioritization and analysis of alternatives is subjective. As with other NATO countries, the majority of Canada's life-cycle cost analysis is focused during the acquisition stages. The Canadian Department of National Defence must submit detailed cost estimates to the Treasury Board at various program stages (e.g., preliminary and effective project approval stages) in order to obtain funding approval. Comparative life-cycle cost models are employed by certain acquisition programs in order to evaluate industry proposals, however life-cycle costs are often appropriated less importance than the acquisition cost during tender selection. Canada's Department of National Defence does not have a dedicated cost analysis group. Acquisition program offices typically employ a small team of financial analysts who generate life-cycle cost estimates. Occasionally external consulting companies are contracted to generate primary and/or secondary acquisition cost estimates. Final program estimates are checked and validated internally, although the level of scrutiny or application of guidelines is unclear.

Turkiye

Turkiye, one of the countries within NATO which has a biggest defence budget according to the percentage of GDP (5-6%), surprisingly has no specific life-cycle cost analysis in the strategic planning process for acquiring the defence capability. The only use of the life-cycle costing in macro analysis is during defence programming and budget which is done occasionally. During identification of defence needs, the life-cycle costing is used only for economic input to make prioritization and sometimes for analysis of alternatives. In Turkiye, the mostly occasional use of life-cycle costing analysis is in the acquisition phase for economical prioritization of procurement alternatives. Despite the use of life-cycle costing analysis in acquisition, there is no requirement or obligation of industry to do life-cycle cost analysis as part of the tender solicitation from industry.

6.0 BEST PRACTICES AND RECOMMENDATIONS

Figure 21 indicates the likely current practice of NATO and PfP nations, with respect to the role of life-cycle cost analysis in defence planning, as culled by SAS-076 from national template surveys (based on responses of seven nations).

	Current Practice of NATO Nations			
MACRO ANALYSIS:	**Universal**	**Typical**	**Uncommon**	**Rare**
Identification of Defence Needs			✓	
Defence Programming and Budgeting		✓		
Acquisition of Materiel Solutions	✓			
MICRO ANALYSIS:				
Identification of Defence Needs			✓	
Mandatory?				✓
Performed?			✓	
Follows Guidelines?			✓	
Used Economic info			✓	
Prioritization		✓		
Affordability assessment		✓		
Analysis of Alternatives		✓		
Defence Programming and Budgeting		✓		
Mandatory?			✓	
Performed?		✓		
Follows Guidelines?		✓		
Used Economic info		✓		
Prioritization			✓	
Affordability assessment			✓	
Analysis of Alternatives			✓	
Acquisition of Materiel Solutions	✓			
Mandatory?		✓		
Follows Guidelines?	✓			
Performed?	✓			
Used Economic info		✓		
Prioritization	✓			
Affordability assessment		✓		
Analysis of Alternatives	✓			

Figure 21: Current practice of NATO nations with respect to the role of life-cycle cost analysis in defence planning.

Based on responses from seven countries, and through a process of vigorous discussion and even heated debate, SAS-076 identified the following best practices with respect to the role played be cost analysis in managing the defence enterprise.

1. **Engage Early-On:**
   In the long run, military power is a function of economic power. Spending imprudently in the short run on unaffordable "gold-plated" weapon systems will add to budget deficits and national debt in the long run. Use cost assessments to inform the strategic decision planning process on what a country can and cannot afford. Canada and Scandinavian countries seem the best practitioners on this score.

2. **Budget and Program to the Cost Estimate:**
   Independent cost estimates and cost assessments are valuable only to the degree they are used. A best practice is to generate an independent life-cycle cost estimate for every major weapon system acquisition program and to reflect this estimate in planning and budgeting systems. This is now a mandatory requirement in the United States Department of Defense for Acquisition Category I programs.

3. **Make Cost the Denominator in Needs and Solutions Analysis:**
   In identifying military needs and solutions, capability-based planning is the gold standard in NATO today. A plethora of techniques are used to assess military value of current and prospective assets including known performance characteristics as well as use of opinions culled from subject matter experts. All too often however, military value is estimated and interpreted without a complete and accurate view of life-cycle costs. A best practice is to compute a return on investment for defence assets defined as:

   $$\frac{\text{Military Value}}{\text{Life-Cycle Costs}}.$$

   It's important to note that risk and balance are other essential dimensions of a complete analysis.

4. **Move to the "Left" in Acquisition:**
   Many, if not all, countries extensively support the acquisition process at key decision points (e.g., "gates" in the United Kingdom, milestones in the United States). However, many cost analysts object to providing cost estimates early in acquisition when systems are only vaguely defined and exist only in design. However, paradoxically, this is when the cost estimates are of the most importance. After all, it is much easier to cancel a bad program that exists only in an analysis of alternatives than an actual program struggling with development or with enormous cost growth in production. Much more extensive cost-analysis support needs to be provided in early design phases. Rough order of magnitude estimates a this point in the life cycle will help empower informed decisions on the allocation of scarce defence assets.

5. **Optimize from an Alliance Perspective:**
   The United States, Canada, and most European nations are facing the dual dilemmas of aging populations, budget deficits and growing national debts that threaten stability. As a consequence, many nations are cutting defence expenditures. Defence spending as a percentage of Gross Domestic Product is approaching lows in contemporary times for many nations. Given pervasive threat to the security of NATO and its alliance members across the broad spectrum of conflict, optimization of military capability seems in order. Duplication of effort, such as several countries possessing extensive sea mine counter-measure capability, might be avoided. Individual Alliance members might develop expertise in a war-fighting domain that could be used to the benefit of the entire Alliance in times of conflict. Savings of hundreds of billions of Euros per annum might be achieved by managing from a NATO enterprise perspective.

6. **Present Decision Makers with Menu of Portfolios:**

Senior defense decision makers express a strong demand for a *menu* of acquisition *alternatives* from which to choose. Heretofore, inordinate attention has been devoted, at high levels, to the management of *individual* acquisition programs. Attention to acquisition details, at high levels, might be better delegated to subordinate authorities in each military department or acquisition community. Senior decision makers, instead, would focus on a complete *set* or *portfolio* of systems in any war fighting or mission area. The portfolio would include science and technology programs, current acquisition programs, and operational systems. Further, alternative portfolios could be defined. These might include:

- A status quo portfolio of currently programmed systems;
- An international portfolio which would leverage assets from a NATO-enterprise point of view; and
- A high-tech portfolio that would emphasize the development and funding of science and technology projects which might, in the long run, yield a competitive advantage on the battlefield.

A review of current and alternative portfolios would shift attention of senior decision makers to where it rightfully belongs, to addressing the fundamental, multiple needs of a ministry of defense, and *trade-off space*, in the face of an entire *spectrum of threats*.

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14. Abstract

Building upon the efforts of SAS-028, SAS-054 and SAS-069, the goal of SAS-076 was to prove the concepts of these earlier RTO SAS works on Life Cycle Cost Analysis by rigorously applying the guidelines to generate sound, reliable, Independent Cost Estimates (ICE) of major weapon system acquisition programs of current, international interest: HMS Rotterdam and HMS Johan de Witt Landing Platform Docks (LPD) of the Netherlands; and NATO's Alliance Ground Surveillance System (AGS).

Innovative, pioneering statistical techniques were employed in these efforts that pushed the state of the art in cost analysis to new frontiers: 1) Decision trees, regression models, and hierarchical clustering, based on scores of technical and performance characteristics, to estimate ship acquisition cost; and 2) Benchmark coefficients of variation coupled with a point estimate to generate a cumulative probability distribution of cost, or S-curve, for NATO AGS.

SAS-076 also ventured into the mélange of defence planning, acquisition, and capability portfolio analysis. SAS-076 surveyed procedures and processes of several NATO and PfP Nations for establishing national security guidance and objectives; for identifying military needs; and for developing and procuring solutions. SAS-076 identified commonalities and differences amongst nations, and it recommended a set of best practices in the cost-analysis domain.

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