Maritime Operational Research Tool Set Review – Final Report

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The information contained herein has been derived and determined through best practice and adherence to the highest levels of ethical, scientific and engineering investigative principles. The reported results, their interpretation, and any opinions expressed therein, remain those of the authors and do not represent, or otherwise reflect, any official opinion or position of DND or the Government of Canada.

Abstract

This project report documents the findings of the Maritime Operational Research Tool Set Review carried out by the Central Operational Research Team as part of its mandate to stimulate intellectual renewal within the Operational Research Division (now the Centre for Operational Research and Analysis). Based on research carried out during Phase 2 of the Review, specific recommendations are given for each of six methodological areas identified as gaps or deficiencies in the maritime operational research tool set. The six methodological areas are listed below.

1. Task Group Effectiveness Modelling
2. Use of Force Planning Scenarios
3. Decision Support and Statistical Advice
4. Costing Analysis and Cost Models
5. Intelligence Surveillance and Reconnaissance Modelling
6. Issues with Detailed Physical Models

Résumé

Le présent rapport de projet décrit les résultats de l’examen de l’ensemble d’outils de recherche opérationnelle maritime réalisé par l’Équipe de recherche opérationnelle centrale (ERO[C]) dans le cadre de son mandat visant à favoriser le renouvellement intellectuel au sein de la Division de la recherche opérationnelle des Forces canadiennes. La recherche effectuée lors de la deuxième étape de l’examen a permis de formuler des recommandations précises pour chacun des six domaines méthodologiques considérés comme des lacunes ou des faiblesses de l’ensemble d’outils de recherche opérationnelle. Ces six domaines méthodologiques sont les suivants :

1. la modélisation de l’efficacité du groupe opérationnel;
2. l’utilisation des Scénarios de planification des forces;
3. l’aide à la décision et les conseils de nature statistique;
4. l’analyse des coûts et les modèles des coûts;
5. la modélisation du renseignement, de la surveillance et de la reconnaissance (RSR);
6. les problèmes relatifs aux modèles physiques détaillés.

Executive summary

As originally directed by the Director General – Centre for Operational Research and Analysis (CORA), The Central Operational Research Team (CORT) undertook a review of the operational research (OR) and analysis capabilities of the maritime OR teams within the Centre. As part of this work, CORT completed a detailed analysis of maritime OR project areas and methodologies, and published the findings under the title of “Phase I of the Maritime Operational Research Tool Set Review, Reference [1]. The phase I study identified six methodological areas that were considered to be deficient or in need of improvement in terms of providing a balanced tool set that address complex problems for the Chief of the Maritime Staff.

This second phase to the study, known as Phase II of the Maritime Review, looked at each of these 6 areas of interest in detail; made observations and recommendations on each are; and published the findings herein under the title of “Maritime Operational Research tool Set Review Final Report.

The six areas of study and the major findings for each are summarized below.

Task Group Effectiveness Modelling

In an ever shifting threat environment, Task Group effectiveness modelling was identified as an area of ongoing interest to the staff of Chief of the Maritime Staff (CMS). The increasing complexity of current and future operations in the littoral poses greater modelling challenges. Current models in CORA such as MARVIN are seen as limited in their ability to deal with neutral shipping and larger C4ISR issues. It was recommended that an experiment with an agent based modelling approach be trialled in an effort to assess task group effectiveness in a littoral environment.

Use of Force Planning Scenarios

This study observed that the use of Force Planning Scenarios (FPS) to place a problem in context was a common practise within many areas of maritime OR. However, it was also noted that the Canadian Forces (CF) Force Planning Scenarios are often not sufficiently detailed for direct use in a maritime OR study; the use of scenarios suffer from a lack of clarity on questions of frequency and concurrency; and observes that there is a need for better documentation of information on frequency, duration, concurrency, and relative importance as they pertain to maritime events. This report recommends that:

Relevant maritime events be documented and classified by scenario;

The frequency, concurrency, and relative importance Force Planning Scenarios used in maritime OR studies be documented;

Modelling of parameter selection over all scenarios using an empirical Bayes analysis be conducted; and,

Make provision for the regular update of a maritime OR Force Planning Scenario database.

Decision Support and Statistical Advice

Decision support and statistical advice are observed to be deeply imbedded in virtually every maritime project that was reviewed in the Phase I report. However, this support is generally provided on an ad hoc basis from within CORT, and it is recommended that expertise in decision support and the provision of statistical advice be institutionalized in the CORT.

Cost Analysis in Maritime OR

This study makes the case that while Maritime OR has historically focussed on efforts to assess operational effectiveness of a system or tactic; it also needs to improve its ability to assess the overall life cycle cost impact of various options. It recommends that CORT explore and trial cost estimation and cost analysis methods in an effort to better define the costs associated with a given level of operational effectiveness.

ISR Modelling

Intelligence, surveillance and reconnaissance, or ISR, enhancements will continue to be a high priority activity. This study observes that ISR modelling at the tactical level is well served by the current OR toolset which includes such applications as Satellite Tool Kit (STK), ARCVIEW, and various MATLAB programs. However, a general purpose system model to evaluate individual and integrated surveillance is lacking. It is recommended that similar efforts that are being made in the Director of Air Staff OR be monitored and that participation by the maritime OR teams in The Technical Cooperation Panel (TTCP) or the North Atlantic Treaty Organization (NATO) working groups are an excellent method of accessing state of the art work and models in this area.

Issues with Detailed Physical Models

This report observes on the value that detailed physical models will continue to have to the operational and tactical levels of maritime OR. It also notes that learning and applying each of these models can take up to a year of a defence scientist's time and associated training costs. It observes that CORA has successfully partnered with some of the Defence Research and Development Canada (DRDC) labs and Canadian Forces Maritime Warfare Center (CFMWC) to build on this training investment and lessen the chance of losing expertise once it has been developed, and recommends that this should continue. It observes that verification, validation and accreditation of thee models is often less then the full industry standard and makes some recommendations as to how to deal with this failing. Finally, given the up front investment in cost, time, and acquired expertise, this study recommends that there may be value in studying alternatives to the current CORA posting policies which centre on moving a scientist every 3-5 years.

Emond, E.J., Hunter, D.G., Taylor I.W., Yazbeck, T,. & Massel, P.L., 2005. Maritime Operational Research Tool Set Review – Final Report. DRDC CORA Technical Memorandum 2005/xx, September 2005.

Sommaire

L’Équipe de recherche opérationnelle centrale (ERO[C]) a terminé l’analyse détaillée des méthodologies et des domaines de projets de recherche opérationnelle maritime et publié ses conclusions dans un document intitulé *Première étape de l’examen de l’ensemble d’outils de recherche opérationnelle maritime*, référence [1]. L’étude de la première étape a recensé six domaines méthodologiques comportant des lacunes ou nécessitant des améliorations dans le but d’offrir un ensemble d’outils équilibrés qui permet de résoudre les problèmes complexes pour le Chef d’état-major des Forces maritimes (CEMFM).

Une autre étude plus détaillée, appelée la « deuxième étape de l’examen maritime », a poussé plus avant l’examen de chacun des six domaines d’intérêt, formulé des observations et des recommandations pour chaque domaine et publié ses conclusions dans le présent rapport final de l’examen de l’ensemble d’outils de recherche opérationnelle maritime.

Voici le résumé des six domaines d’étude et des principales conclusions.

Modélisation de l’efficacité du groupe opérationnel

Dans un contexte où la menace évolue constamment, la modélisation de l’efficacité du groupe opérationnel a été choisie comme domaine d’intérêt actuel pour le personnel du CEMFM. La complexité grandissante des opérations en cours ou à venir sur le littoral pose des défis de modélisation encore plus importants. Les modèles existants de la Division de la recherche opérationnelle (DRO), comme MARVIN, semblent avoir de la difficulté à s’occuper des navires neutres et à résoudre les problèmes plus importants liés au commandement, au contrôle et aux communications du renseignement, de la surveillance et de la reconnaissance par ordinateur (C4ISR). Il est recommandé de mettre à l’essai une approche de modélisation en mode agent pour évaluer l’efficacité du groupe opérationnel dans un milieu littoral.

Utilisation des Scénarios de planification des forces

Selon l’étude, l’utilisation des Scénarios de planification des forces pour la mise en contexte d’un problème est une pratique courante dans bien des domaines de la recherche opérationnelle maritime. Toutefois, l’étude a révélé que les Scénarios de planification des forces des Forces canadiennes (FC) sont rarement assez détaillés pour pouvoir être utilisés directement dans une étude de recherche opérationnelle maritime, que l’utilisation des scénarios manque de clarté sur les questions de la fréquence et de la simultanéité et qu’il faut mieux consigner les renseignements sur la fréquence, la

durée, la simultanéité et l'importance relative, car ils sont liés aux événements maritimes. Ce rapport recommande les éléments suivants :

consigner les événements maritimes et les classer par scénario;

enregistrer la fréquence, la simultanéité et l'importance relative des Scénarios de planification des forces utilisés dans les études de recherche opérationnelle maritime;

modéliser la sélection des paramètres pour tous les scénarios qui utilisent une analyse empirique de Bayes;

prendre des mesures pour mettre régulièrement à jour la base de données des Scénarios de planification des forces de la recherche opérationnelle maritime.

Aide à la décision et conseils de nature statistique

L'aide à la décision et les conseils de nature statistique sont profondément intégrés dans la presque totalité des projets examinés par le rapport de la première étape. Toutefois, cet appui est généralement offert de manière ponctuelle au sein de l'ERO(C); il est donc recommandé d'institutionnaliser les connaissances sur l'aide à la décision et la formulation de conseil de nature statistique dans l'ERO(C).

Analyse des coûts de la recherche opérationnelle maritime

Selon l'étude, la recherche opérationnelle maritime a traditionnellement concentré ses efforts sur l'évaluation de l'efficacité opérationnelle d'un système ou d'une tactique, mais elle doit aussi accroître sa capacité à déterminer l'incidence du coût du cycle de vie global de différentes options. L'étude recommande à l'ERO(C) d'examiner et de mettre à l'essai des méthodes d'analyse des coûts afin de mieux établir les coûts associés à un niveau donné d'efficacité opérationnelle.

Modélisation du renseignement, de la surveillance et de la reconnaissance (RSR)

Les améliorations du RSR demeurent une activité prioritaire. Cette étude révèle que l'ensemble d'outils de recherche opérationnelle actuel répond adéquatement aux besoins de la modélisation du RSR au niveau tactique; cet ensemble inclut des applications comme le Satellite Tool Kit (STK) et ARCVIEW et différents programmes MATLAB. Toutefois, il manque un système de modèle polyvalent pour évaluer la surveillance individuelle et intégrée. Il est recommandé de surveiller les efforts semblables qui sont faits par le Directeur – Recherche opérationnelle (Force aérienne) et de favoriser la participation des équipes de recherche opérationnelle maritime aux groupes de travail du programme de coopération technique, car il s'agit d'un excellent moyen pour découvrir les modèles et les travaux de pointe dans ce domaine.

Problèmes relatifs aux modèles physiques détaillés

Ce rapport examine la valeur que les modèles physiques détaillés continueront d'avoir pour les niveaux opérationnel et tactique de la recherche opérationnelle maritime. Il souligne aussi que l'apprentissage et l'application de ces modèles peuvent demander aux scientifiques de la défense jusqu'à une année de travail, sans compter les coûts de formation connexes. Il fait remarquer que la DRO a réussi à mettre en place des partenariats avec quelques-uns des laboratoires de Recherche et développement pour la défense Canada (RDDC) et le Centre de guerre navale des Forces canadiennes (CGNFC) afin de prendre appui sur cet investissement dans la formation et de réduire les risques de perte des connaissances acquises; il indique qu'il faut poursuivre cette pratique. Il fait observer que la vérification, la validation et la reconnaissance de ces modèles sont souvent inférieures à la norme industrielle et propose certaines recommandations pour combler cette lacune. Finalement, compte tenu de l'investissement initial en temps, en argent et en connaissances acquises, cette étude recommande d'examiner d'autres solutions de rechange aux politiques d'affectation actuelles de la DRO qui se concentrent sur le déplacement des scientifiques tous les trois à cinq ans.

EMOND, E. J., D. G. HUNTER, I. W. TAYLOR, T. YAZBECK et P. L. MASSEL. *Examen de l'ensemble d'outils de recherche opérationnelle maritime – Rapport final,* rapport technique de l'ERO(C) de RDDC, 2005, 2005/28.

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1. Introduction

The Central Operational Research Team (CORT) has been given the task of stimulating intellectual renewal within the Operational Research Division (CORA). As part of this mandate CORT has undertaken periodic reviews of the modelling and simulation tool set used within each client area. The purpose of these reviews is to ensure that the tool sets used to conduct operational research and analysis are the best fit both scientifically and practically and to make recommendations for change if warranted.

Preliminary work on the Maritime Operational Research Tool Set Review began early in 2003. (For purposes of economy, the phrase Maritime Review will be used throughout this report instead of the more formal name.) Due to staff changes and other factors, for practical purposes the Maritime Review began in earnest in September 2003.

Phase One consisted in part of a detailed analysis of maritime operational research (OR) project areas and methodologies using a combination of structured interviews with current and former maritime OR analysts and literature review where necessary. This methodology was developed as a result of constraints due to time pressures as well as security clearance issues. The results of this research were documented in Reference [1].

In addition to the project area and methodology analysis, Phase One included an assessment of the future strategic environment. This strategic assessment covered the history of Canadian maritime OR, future issues for the Canadian Navy, and maritime OR in other countries. The strategic assessment was documented in Reference [2].

Operational Research relies on abstract mathematical models to analyze problems and provide quantitative scientifically based advice to clients. Models and other OR methodologies are key to providing quality and timely OR advice. Given the wide variety of current and future project areas found in Phase One of the Maritime Review, our overall objective in this report is to ensure continued quality support to our naval sponsors by providing a variety of flexible OR tools and to encourage creativity and adaptability in the maritime OR analysts.

1.1 Phase One Findings

The strategic assessment, Reference [2], noted the short-term nature of much of the OR program, reflecting the traditional OR pattern of providing timely advice to our clients on a wide variety of issues. It identified two emerging areas which are already having an impact on the maritime OR program. The first of these is the force structure of the future which will be capability-based, affordable, sustainable, and will reflect the strategic vision for the future navy. The second emerging area is operations in the littorals and includes interdiction, blockade, border patrols, port security, support to land based operations, and self-defence against asymmetric threats. Reference [2] concluded that the maritime operational research organization is mature and successful, with a high level of client confidence and uses state of the art methods. In addition it concluded that the current structure of the maritime OR teams is well suited to provide OR support to the navy both at National Defence Headquarters

(NDHQ) and the two coasts[1]. Sustainability and staff transition issues exist but were beyond the scope of the Maritime Review. Finally, Reference [2] stressed the importance of maintaining and improving working relationships with others conducting maritime OR and R&D through The Technical Cooperation Panel (TTCP) and through the North Atlantic Treaty Organization (NATO).

The detailed analysis of the maritime OR project areas and methodologies reported in Reference [1] showed that the maritime OR teams are flexible, able to quickly react to the needs of sponsors with a variety of OR methods and tools. In total Reference [1] noted 77 maritime OR projects and 61 OR methods. The three maritime OR teams are less reliant on large models than other client areas and the current maritime OR tool set is versatile and state of the art in most cases. Reference [1] also noted some methodological gaps and deficiencies. These were the main focus of Phase Two of the Maritime Review.

1.2 Gaps and Deficiencies

Phase Two of the Maritime Review consisted of detailed research on each of six methodological areas identified in Phase One as gaps or deficiencies in the maritime OR tool set. This report will document the findings of Phase Two of the Maritime Review and present specific recommendations in each area for implementation in Phase Three[2]. The six methodological areas are listed below.

1. Task Group Effectiveness Modelling
2. Use of Force Planning Scenarios
3. Decision Support and Statistical Advice
4. C4ISR Modelling
5. Costing Analysis and Cost Models
6. Issues with Detailed Physical Models

Specific findings and recommendations on each of these six areas are presented in the following sections followed by a summary. An annex on each area has been included giving more details from the background research.

[1] Nevertheless, at the time of publication, the roles of the OR teams currently supporting the navy is being revisited as a result of the reorganization and transformation efforts initiated by the Chief of the Defence Staff,: specifically the stand-up of CANADA Command, the Canadian Forces Transformation Team, and Canadian Expeditionary Forces Command.

[2] Phase III was a proposed work program to address the recommendations made in this report. At the time of publication, some initiatives have been attempted but many have been suspended by higher priority work arising from the needs of the effort to support the analysis and implementation of the CF Vision.

2. Task Group Effectiveness Modelling

Task group effectiveness modelling was identified as an area for further research in Phase One of the Maritime OR Tool Set Review primarily based on the anticipation of high priority taskings to the Maritime OR Team (MORT) to assess proposed task group structures of the future and the scarcity of suitable OR tools in this area. In terms of the project categories defined in Phase One of the Maritime Review, task group effectiveness studies fall under Projects Involving Multiple Maritime Assets in a Hostile Environment. From Reference [1]:.

> *" … (This category involves) multiple assets and threats and their interactions with one another, typically at the Task Group level. Methodologically, projects in this category use Non-Physics Based Simulations, considering the situations and scenarios more abstractly than the Projects Involving Individual Maritime Assets in a Hostile Environment but less so than Maritime Force Capability Projects. The usual output of such studies is recommendations on the most effective compositions of Task Groups. There were three projects in this category."*

Two of the three projects identified in Phase One in the category "Multiple Maritime Assets in a Hostile Environment" were in MORT and the other one was in the Maritime Forces Atlantic OR Team. The first MORT project was on Maritime Helicopter Fleet Sizing, sponsored by the project management office for the maritime helicopter project in 1999. This project used ANSWER, a detailed physical model from QinetiQ to evaluate helicopter-submarine interactions; HeloSim, a scheduling model developed by MORT for this study; and MARVIN, a high-level discrete event simulation also written specifically for this project. MARVIN has been further developed into a useful general-purpose model. Development of MARVIN is continuing using external contracting.

The second MORT project in the category "Multiple Maritime Assets in a Hostile Environment" is an ongoing general study sponsored by the Director of Maritime Strategy (D Mar Strat) entitled Task Group Effectiveness. Preliminary work on defining the problem using literature review, strategic review and historical review of CF operations has been completed. The use of Planning Scenarios, the Ship Air Defence Model (SADM) and the MARVIN model is anticipated.

The Maritime Forces Atlantic (MARLANT) project in the "Multiple Maritime Assets in a Hostile Environment" category was a 2001 study of Naval Force Missile Defence against dual-mode seeker missile threats during a NATO exercise sponsored by N3 MARLANT and the Canadian Forces Maritime Warfare Centre (CFMWC). The methodology for this study was to use an analytical approach accompanied by a MATLAB application

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2.1 Increasing Complexity of Future Task Group Effectiveness Studies

The Phase One Strategic Review, Reference [2], identified a requirement to assess naval task group effectiveness issues in the littorals. This adds significantly to the complexity of the problem as compared to open ocean situations. Some of the issues identified are near shore interdiction operations, blockade, border patrols, port security, support to land-based operations and self-defence. In addition the problem of neutral actors is immensely more difficult in the littorals. There is a requirement to advance beyond traditional physical interaction based OR models and consider outcomes with red forces, blue forces and possibly neutrals reacting to each other in complex ways.

The added complexity of task group effectiveness assessment in the littorals implies that previous models, such as MARVIN, are likely inadequate for this purpose. Therefore, the use of agent-based methods has been explored. Annex A reports on the Phase Two research conducted on Task Group Effectiveness Modelling. It recommends that the New Zealand Map Aware Non-uniform Automata (MANA) model be assessed as a potentially useful addition to the Maritime OR tool set to explore task group effectiveness modelling. Besides allowing for the complexity of task group operations in the littorals, MANA would allow the inclusion of net-centric warfare issues, albeit in a distilled or generic manner.

2.2 Recommendation

Task group effectiveness modelling is an area of increasing importance for maritime OR, particularly in MORT. The MARVIN model is capable of assessing task group effectiveness in the open ocean but is not adequate for the littorals nor does it handle neutrals or C4ISR issues. It is therefore recommended that a demonstration project be carried out by CORT in conjunction with MORT and D Mar Strat to assess the utility of an agent-based model to assess task group effectiveness in a littoral environment.

CORT will provide the lead analyst for the proposed project but will require participation by an experienced MORT analyst for guidance and subject matter assistance. In addition, participation by an officer from D Mar Strat will be necessary in order to insure that the chosen project is relevant to the Navy.

In addition to providing a relevant example of the capabilities and advantages of agent-based modelling to the Maritime Forces, the project will benefit the wider CORA audience in demonstrating a state of the art modelling technique which may be applicable in a wide variety of operational research problems.

3. Use of Force Planning Scenarios

The departmental force planning scenarios (FPS) are defined in Reference [13] as:

> *" (…) an outline of a planned series of events (real or imagined) that include specifications as to the various scenes and situations, the cast of characters and detailed direction for the stage setting and the development of the events."*

Force planning scenarios were observed as a methodology in 10 separate projects in Phase One of the Maritime Review, making them one of the most frequently used OR tools (see Annex B for details of these studies.) The force planning scenarios are important in many studies because they are used to put OR problems in an operational and strategic context. In a many of these studies, the scenarios were a framework for more precise analysis and assessing the relative importance of the different scenarios often proved to be a difficult problem to reconcile.

Because it is not the purpose of the FPS to identify the likelihood of potential future conflicts, a prioritization of scenarios was deliberately left out during the development of the FPS. However, is clear that that such a measure is necessary to make reasonable modelling predictions and is often calculated by the analysts involved on an ad hoc basis with the best information available at the time.

The official departmental force planning scenarios are in most cases not sufficiently detailed or focused for direct use in maritime OR studies. For this reason it is most often necessary to develop more specific sub-scenarios or vignettes for use in studies. The following quote from the High Frequency Surface Wave Radar (HFSWR) – Operational Evaluation study by Dore and Fong, Reference [65], illustrates this point.

> *"… four scenarios were selected that require significant ISR capability: Search and Rescue, Surveillance, National Sovereignty, and Defence of North America. As these scenarios are too general in nature to provide a straightforward evaluation of the sensor system, maritime vignettes were produced for each of the four ISR scenarios …"*

In order to be practically useful in OR studies, each scenario or vignette requires inputs specifying its frequency of occurrence over time and its duration. Further, there is often a requirement in studies to consider the possible simultaneous occurrence of different scenarios, including the possibility of overlapping occurrences of the same type of scenario.

The review team has concluded that given the importance of force planning scenarios to maritime OR studies, there is a need for a source of information and guidance on their use. In addition to the need for documentation of information on frequency, duration, simultaneous occurrence and relative importance, there is a requirement to make the use of scenarios in maritime OR studies more consistent and analytically sound.

3.1 Recommendation

It is recommended that either an external contract or an internal project be approved to create and document a permanent source of information and guidance on the use of planning scenarios in Maritime OR. Specific details include the following.

a. Research and document all relevant maritime historical events and classify by scenario;

b. Research and document all use of force planning scenarios in maritime OR studies including the use of vignettes, noting the specific parameters used such as frequencies and relative importance;

c. Use an Empirical Bayes analysis to model parameter selection over all scenarios with a detailed example; and,

d. Make provision for regularly updating a maritime OR force planning scenario database.

It also recommended that this effort be done in concert and be consistent with the Directorate of Defence Analysis's ongoing efforts to maintain and update the Force Planning Scenarios that are used as a base for department wide analytical efforts.

4. Decision Support and Statistical Advice

Expert advice on state of the art decision support and statistical methodologies is vital for CORA in general, including all maritime OR teams. In virtually every maritime OR project in Phase One of the Maritime Review there were elements of both areas. Annex C provides details of maritime OR projects in which the use of decision support methods was a main feature. In addition, Annex C documents research on several issues in this area as well as a brief description of specific methodologies.

Although expertise in both decision support and statistics exists and is available on an ad hoc basis from CORT and from individuals in other teams, the provision of advice and assistance to OR scientists who need to use these methods is could be more formally institutionalized in CORT. In particular this type of assistance, while acknowledged in the CORT mandate and business plan, could be more formally confirmed and managed within the overall mandate of CORT.

4.1 Recommendation

It is therefore recommended that CORT be given a clearer mandate to the development and maintenance of state of the art decision support and statistical expertise. The provision of dedicated support in these areas should be made clearer in CORT's business plan.

5. Cost Analysis in Maritime OR

Cost analysis and cost modelling were identified as an area of deficiency in Phase I of the Maritime OR Tool Set Review. From the Phase I report, Reference [1].

> *"Cost analysis identifies the cost implications of decisions and is an integral part of force structure analysis as well as the acquisition process for military systems of all types. The CORT Maritime OR review found little evidence that any of the Maritime OR teams are providing costing analysis as part of their operational research studies and no specific cost estimation models were observed other than the Three Point Estimation Method used in a recent MARPAC study. Although cost figures do appear in some studies, these are typically summary values provided by the study sponsors and not analyzed in any detail in the study report."*

Cost analysis was included in Phase II as an area of deficiency in the Maritime OR tool set on the basis that we did not observe the amount of activity in this area that we had expected. This is especially so given the importance placed on the effectiveness and affordability of the future navy by the Chief of the Maritime Staff, Reference [69].

5.1 Is Cost Analysis an OR Activity?

Although quantitative cost data are ubiquitous in Operations Research, cost estimation and cost analysis as specific methodological areas are rarely given more than cursory treatment in textbooks. However, there is little doubt that these topics are of fundamental interest to decision makers, particularly in government and the military. For example, the US Air Force Analyst's Notebook, Reference [68], includes a detailed chapter on the theory and methods of cost analysis entitled "Estimating Costs" and it states:

> *"No analyst can afford to ignore cost. Cost is most certainly a measure of goodness, but a measure that must eventually be combined with measures of effectiveness to be fairly assessed."*

Further, from the George Mason University School of Information Technology and Engineering, Department of Operations Research and Engineering, Reference [75]:

> *"Cost Analysis is a sub-discipline of Operations Research. While drawing on other disciplines (e.g., Managerial Accounting, Econometrics, Systems Analysis, etc.), Cost Analysis uses the basic tools of Operations Research to solve a specific class of public sector problems. Cost Analysis is an inquiry to assist decision-makers in choosing preferred future courses of action by evaluating selected alternatives on the basis of their costs, benefits, and risks. Cost Analysis is distinctly different from Cost Estimating in that projecting future courses of action usually requires mathematical modelling, hence the link to Operations Research and Economic Analysis."*

Given the importance of cost estimation and cost analysis to government and military decision making, it is our conclusion that this area constitutes a gap in the maritime operational research tool set. Indeed, there is a noticeable lack of activity in this area throughout the OR division, with some exceptions, notably in the logistics area. Work in this area has in the past more often been left to financial planning expertise in ADM Fin or DFPPC; agencies that aren't functionally responsive to the needs of the Maritime Staff when it comes to cost estimation of future force structures. Thus, the area of cost estimation may be an area that the OR division should consider as an area of potential growth.

Annex E to this report gives the results of research conducted on costing and cost analysis in the Operational Research Division historically as well as indicating current departmental resources in this area. It also provides a discussion of several approaches to the analysis of cost-effectiveness in a military OR context.

5.2 Recommendations

It is recommended that cost estimation and cost analysis methods and tools be explored by CORT with a view to raising awareness of these tools throughout CORA and providing a demonstration of their utility in Maritime Operational Research.

More specifically, it is recommended that CORT, in conjunction with MORT and one or more Navy sponsors, acquire and apply cost estimation and cost analysis methodologies and tools to a suitable current Maritime OR project. CORT would investigate and apply cost estimation methods and tools to the extent that these are necessary for the application of cost analysis and do not needlessly duplicate current departmental resources in this area.

In order to implement this recommendation there are two pre-requisites. Although CORT will provide a senior analyst to lead the project, participation by MORT and the Canadian Maritime Forces would be required to provide a suitable demonstration project and be available to give advice when required. In addition, financial resources up to approximately $100,000 Ca would be required from the Navy or other sponsor for the purchase of software and associated training.

6. ISR Modelling

The primary purpose of projects in the category Projects Concerned with Intelligence, Surveillance and Reconnaissance (ISR) observed upon in Phase One of the Maritime Review was improving the maritime situational awareness of the Canadian Forces. ISR was the single most observed project category in Phase One of the Maritime Review comprising 19 out of a total of 77 projects. There were 4 ISR projects at MORT and MARLANT and 11 at the Maritime Forces Pacific (MARPAC).

A wide variety of OR methodologies were employed on maritime ISR projects. In order of decreasing observed frequency of employment, the 12 methodologies observed in Phase One of the Maritime Review were: Data Collection (12), General Purpose Toolkit (10), Data Analysis (4), Non-Physics Based Simulations (3), Software Engineering (3), Force Planning Scenarios (2), Knowledge Base Construction (2), Detailed Physical Models (1), Decision Support (1), Mathematical Optimization (1), Risk Analysis (1), and Experimental Design (1).

ISR modelling has been identified as an area of deficiency in the Maritime OR tool set Reference [1]:

> *"Improvements to and analysis of the Maritime Picture continue to be a priority for all three Maritime OR teams, especially MARPAC and MARLANT. Although much has been done to analyze and model ISR, particularly in Victoria where this is a high priority, there is a need for a general purpose surveillance model capable of evaluating the relative contributions of the entire spectrum of surveillance assets to the Recognized Maritime Picture. In addition the model may be capable of assisting OR analysts in analyzing assets such as maritime patrol aircraft by providing functionality to handle routings and timings as well as target modelling. The SURPASS model developed by TNO in the Netherlands is a model of interest and may be a good starting point for a general purpose Canadian surveillance model."*

Annex D to this report discusses some of the ISR models researched for Phase Two of the Maritime Review. SIMLAB is recommended for ISR projects in which detailed physical modelling is appropriate. Exploration of the MANA model for some types of ISR projects is also recommended. The SURPASS model was found to be less useful and was not recommended.

6.1 Recommendations

ISR will continue to be a high priority area of activity for the Navy and in all three Maritime OR teams, particularly in MARPAC. The current maritime OR toolset including state of the art general purpose software packages such as STK, ARCVIEW and MATLAB is adequate for most tactical level ISR projects.

SIMLAB is a detailed physics based model which has been used effectively in ISR projects in which this type of modelling is required and appropriate. It is recommended that MORT continue to cooperate with Defense Research and Development Canada (DRDC) Ottawa in using and developing SIMLAB.

There is a lack of a general purpose system model to evaluate the effectiveness of individual and integrated surveillance assets within a system context. However, such a model is currently under development within the Director Air Staff OR Team (DASOR). Discussions with DASOR have indicated that the proposed model is at the appropriate level of detail. It is therefore recommended that MORT, MARLANT and MARPAC monitor and participate to the extent possible in the development and testing of the DASOR maritime surveillance model.

Finally, it is recommended that the Maritime OR teams continue their current participation in TTCP working groups and expand its participation in similar NATO activities as the best way to access state of the art modelling and progress in the area of Netcentric Warfare.

7. Issues with Detailed Physical Models

Detailed physical models were defined in Reference 1 as models of the physical environment that use high-fidelity algorithms and an accurate model of dynamics. Six detailed physical models were observed in Phase One of the Maritime Review. These are listed in Table 1 below along with the number of projects in which each was used by the three Maritime OR teams.

TABLE 1: DETAILED PHYSICAL MODELS

Model Name	Model Domain	MARLANT Projects	MORT Projects	MARPAC Projects
ODIN	Underwater Warfare	2	2	0
SADM	Ship Air Defence	1	3	0
SIMLAB	Radar	0	1	0
ANSWER	Antisubmarine Warfare	0	2	1
POSEIDON	Mine Analysis	1	0	0
MSSM	Sonar Search	1	0	0

Detailed physical models were primarily used in Maritime OR projects in the category "Projects Involving Individual Maritime Assets in a Hostile Environment". High fidelity models are appropriate and often essential for this project category and for the very similar categories "Antisubmarine Warfare Projects" and "Threat Modelling". Although ISR projects normally do not require detailed physical modelling, the SIMLAB model was used in the MORT High Frequency Surface Wave Radar Comparative Study and is likely to continue to be useful in specific ISR projects either by itself or to produce inputs and parameters for ISR system studies in the future.

7.1 Issues

Detailed physical models, in particular SADM, ODIN, and SIMLAB will continue to be essential tools for Maritime operational research in the future, both as study vehicles and as repositories of knowledge. Funding as well as technical development and the provision of data have been obtained cooperatively from the CFMWC, DRDC Atlantic, and DRDC Ottawa.

As noted in Reference 1, extensive training and familiarization periods are required for OR analysts to become competent with detailed physical models and there has been concern expressed over the retention of trained analysts in view of the small size of the Maritime OR teams and the frequency of staff rotations imposed by the Defence Science career progression. An issue which may have an impact on the use of detailed physical models in Maritime Operational Research in the future is the verification, validation and accreditation processes being proposed for certain simulation models by the Synthetic Environment Working Group. This issue is discussed in more detail in Annex F.

7.2 Recommendations

Despite the high cost to the Maritime OR teams in terms of training and familiarization, detailed physical models, in particular SADM, ODIN and SIMLAB are essential tools and repositories of knowledge and should continue to be part of the Maritime OR tool set. Current cooperation with both CFMWC and the DRDC laboratories has been beneficial in the past, particularly for MARLANT and MORT. The strengthening of ties with CFMWC and the DRDC laboratories is already occurring and is an essential element of the continued successful use of detailed physical models in CORA. It is recommended that we continue to foster cooperation with DRDC Atlantic, the CFMWC, DRDC Ottawa and others for expertise, data and funding with respect to detailed physical models in order to ensure that these essential tools remain part of the Maritime OR tool set.

The cost to the relatively small Maritime OR teams in terms of up to one year of training and familiarization with detailed physical models appears to be unavoidable. A partial remedy to this problem is possible through the use of systematic exploratory analysis consisting of extensive computer experiments to determine the sensitivity of model outputs to changes in input parameters thus giving new analysts a head start in terms of their understanding of model behavior. Such a program would likely be expensive in analyst effort and would only make sense if exploratory analysis becomes an acceptable surrogate for model verification, validation and accreditation in the future. Therefore it is recommended that if verification, validation, and accreditation becomes a serious issue for CORA with respect to our use of detailed physical models in Maritime OR, exploratory analysis be investigated as a methodology.

Although there has been reluctance in the past to discuss modification of the CORA posting policies, it is clear that there are fundamental conflicts between the needs of the individual Defence Scientist and CORA versus the requirement to provide the best possible OR advice and analysis to the Canadian Naval Forces. Because of their own posting policies and practices, the Navy is very understanding of this problem and of the requirement to rotate personnel for the overall good of the system. Modernization and rationalization of the posting policy is a topic entirely suitable to operational research analysis and there may be ways to make the system more efficient and effective both for the Defence Science group and the Navy. It is therefore recommended that CORA sponsor either an internal study by CORT or an external contract by qualified consultants to explore ways to improve both the effectiveness of the Defence Science career progression as well as the provision of OR analysis and advice to the Navy.

8. Summary of Recommendations

Specific recommendations have been made for each of six areas of gaps or deficiencies noted in the CORT Maritime OR Tool Set Review. It is our intention to action all of the recommendations where feasible as Phase 3 – Implementation of the Maritime Review. A summary of the recommendations is given below.

Task Group Effectiveness Modelling

It is recommended that a demonstration project be carried out by CORT in conjunction with MORT and D Mar Strat to assess the utility of an agent-based model to assess task group effectiveness in a littoral environment. CORT will provide the lead analyst for the proposed project but will require participation by an experienced MORT analyst for guidance and subject matter assistance. In addition, participation by an officer from D Mar Strat will be necessary in order to insure that the chosen project is relevant to the Navy.

Use of Force Planning Scenarios

It is recommended that, in close coordination with DDA, either an external contract or an internal project be approved to create and document a permanent source of information and guidance on the use of planning scenarios in Maritime OR.

Decision Support and Statistical Advice

It is recommended that CORA confirm its commitment to fostering the development and maintenance of state of the art decision support and statistical expertise and that these vital capabilities be institutionalized in the Central OR Team.

Cost Analysis in Maritime OR

It is recommended that cost estimation and cost analysis methods and tools be explored by CORT with a view to raising awareness of these tools throughout CORA and providing a demonstration of their utility in Maritime Operational Research.

More specifically, it is recommended that CORT, in conjunction with MORT and one or more Navy sponsors, acquire and apply cost estimation and cost analysis methodologies and tools to a suitable current Maritime OR project.

ISR Modelling

It is recommended that MORT continue to cooperate with DRDC Ottawa in using and developing SIMLAB.

It is recommended that MORT, MARLANT and MARPAC monitor and participate to the extent possible in the development and testing of the DASOR maritime surveillance model.

It is recommended that the Maritime OR teams continue their current participation in TTCP working groups as the best way to access state of the art modelling and progress in the area of Netcentric Warfare.

Issues with Detailed Physical Models

It is recommended that we continue to foster cooperation with DRDC Atlantic, the CFMWC, DRDC Ottawa and others for expertise, data and funding with respect to detailed physical models in order to ensure that these essential tools remain part of the Maritime OR tool set.

It is recommended that if verification, validation, and accreditation becomes a serious issue for CORA with respect to our use of detailed physical models in Maritime OR, exploratory analysis be investigated as a methodology.

It is recommended that CORA sponsor either an internal study by CORT or an external contract by qualified consultants to explore ways to improve both the effectiveness of the Defence Science career progression as well as the provision of OR analysis and advice to the Navy.

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Annex A: Task Group Effectiveness Modelling

The set of models currently in use for maritime operational research was documented in Reference 2. While Reference 2 did not specifically categorise models used for task group effectiveness, most of the models currently used for task group studies fall into the detailed physical model (DPM) or non-physics based simulations categories. As noted in Reference 2 the model that currently comes closest to fulfilling this need is MARVIN (**MAR**itime **VI**g**N**ette), (References 3 and 4), a product of the Operational Research Division.

MARVIN is a discrete event simulation that models a combat encounter between a Blue Task Group and a Red Task Group. The task groups of both sides may be composed of a collection of surface vessels, helicopters, submarines and fixed wing aircraft. Events and interactions in MARVIN are resolved abstractly rather than modelling the physical processes involved. As such, it falls into the Non-Physics Based Simulation category of model defined in Reference 2.

Since the submission of Reference 2 for publication, a contract has been let with the objective of making major modifications to MARVIN (Reference 5). When completed, these modifications will substantially extend the capabilities of MARVIN. (See Annex A of Reference 5 for details.)

Agent-based Models

The growing use of agent-based models and the study of complex adaptive systems are some of the most exciting new developments in military simulation and modelling over the past decade. The United States Marine Corps Warfighting Laboratory's Project Albert (Reference 6) provides an excellent repository of information and links. Using the concepts of chaos and complexity theory, models such as ISAAC (**I**rreducible **S**emi-**A**utonomous **A**daptive **C**ombat) (Reference 7) and EINSTein (**E**nhanced **I**SAAC **N**eural **S**imulation **T**ool) (References 8 and 9), focus on simulating the soft or intangible factors of warfare, such as human behaviour and information flow, that have been pivotal factors in historical conflicts, by modelling the interactions between autonomous agents. These agents make decisions about their actions based on a set of rules or preferences defined by the researchers. An excellent description of advantages of agent-based models can be found in Reference 10:

> *"Over the past couple of decades there has been an increasing realisation that the conventional operations research tools based on rigorous mathematical equations and detailed physical descriptions of combat cannot provide a realistic description of the complex and dynamic situations in which military operations are conducted."*
>
> *"The main drawback of equation-based models (EBM) is that they are incapable of dealing with the dynamics of interactions between the combating sides and their reactions to each other's actions. Another serious challenge to EBM is that the world is fundamentally non-*

linear and consequently many problems defy the traditional scientific approach of analysis by decomposition."

"Agent-based models offer an opportunity to analyse the aforementioned complexity problems by concentrating on the behaviour of and interaction between the participating entities instead of the performance of specific weapons or sensor systems. In other words we shift our attention from analysing the performance of pieces of equipment to how different modes of operation may alter the outcome of a combat or peacekeeping or how the C2 system utilises information and acts upon it, and the consequence on the success or otherwise of a mission. In summary, we concentrate on the emergent pattern of the whole rather than the individual parts." (Author's emphasis)

David P. Galligan, Mark A. Anderson and Michael K. Lauren of New Zealand's Defence Technology Agency have developed an excellent example of an agent-based simulation, called Map-Aware Non-Uniform Automata, or MANA (Reference 11). MANA has been used to study a wide variety of subjects, from swarm attacks on maritime forces by fast attack craft (Reference 12) to command and control (C2) effectiveness (Reference 10) to emergency food distribution strategies (Reference 13). MANA has three features that make it especially interesting. The first is the trigger point, which allows an agent to change its behaviour based on events that happen to or are done by the agent. The second is the Situational Awareness map, where the agent's information about other agents is collected. The flow of this information to other agents can then be controlled and manipulated to simulate a variety of battlefield phenomena. The third is the ability to have terrain maps that affect the ability of the agent to move, sense and engage in combat. These three abilities make MANA ideally suited to model scenarios that are not handled well by EBM, such as maritime interdiction operations, and operations other than war, where the primary problem is not one of technical system performance but of the interaction of the different actors.

The agents' abilities are represented abstractly in the model. For example, weapon systems are given a simple probability of hit or kill, a range and burst radius (as appropriate), sensors are given probabilities of detection and classification as a function of range, and the agents themselves have a protection rating and movement speeds[3]. At no point is any physical process modelled in any way, resulting in a very quick execution time per iteration of a scenario. MANA also has the capability of varying these parameters over a given range in a controlled fashion. This process is known as data farming (Reference 14). Taken together, this allows the user to search a very wide range of the parameter space in a reasonable period of time and to perform a sensitivity analysis on the parameter values.[4] Indeed, MANA is a stochastic model, and therefore a large number of iterations of the scenario are necessary to obtain a reliable indication of the trend(s).

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[3] These are a subset of the characteristics of the mentioned systems and agents, given for illustrative purposes only.

[4] It should be noted that these features are common to many agent-based models, not only MANA.

Finally, MANA is also very easy to learn and to use. The learning curve for the program is shallow, and configuring a new scenario of considerable sophistication can be done in a remarkably short period of time. This, together with the advantages and capabilities described above, leads the author to recommend that the Operational Research Division investigate this model for use within the Division.

MARVIN and MANA share many characteristics and will be more similar after MARVIN's improvements. However, MARVIN has a greater focus on combat than does MANA. MANA is a higher-level model and it places more emphasis on the issues of command, control, and communications and behavioural issues. MANA's agents are less rigidly locked into their planned behaviour and actions than are MARVIN's platforms.

Synthesis

There are obvious areas of operational research in which agent-based models are not appropriate or are inadequate in comparison with Equation-Based Models. Examples of such areas are electronic warfare and anti-ship missile defence, ballistics and torpedo motion analysis. All of these situations are characterised by minimal human involvement and being dominated by physical interactions.

The best of both worlds can be had by integration of the two types of models to take advantage of their complementary strengths. An excellent example of this is found in Reference [12], wherein the results of various models are compared and validated against one another. Using agent-based models to perform the higher-level modelling and the equation-based models to feed the critical parameters (e.g., weapon kill probabilities and sensor system detection and classification probabilities) to the agent-based model and validate the results of the agent-based model with selected test scenarios is likely the optimal procedure.

Conclusions

It is concluded that there is no significant lack of Task Group Effectiveness modelling capability from the EBM side. Models such as SADM and ODIN are available, within the limitations previously discussed in Reference 2. Additional effort in the research & development or acquisition of this type of model beyond the current level is not necessary.

The other side of the Task Group Effectiveness modelling equation, the Non-Physics Based Simulations, have been and are improving with the development of MARVIN and the planned upgrades to it. Having reviewed a number of Agent-Based Models, it is considered that the adoption of MANA would be advantageous to the Division because of its ease of use and its strengths in the simulation of intangible factors.

The most important objective should be a synthesis of the two approaches that recognizes the strengths and weaknesses inherent to each. By using the two types of model in conjunction the quality and timeliness of CORA studies can be improved.

Annex B: Force Planning Scenarios

The departmental force planning scenarios (FPS) are defined in Reference [13] as:

> *" (…) an outline of a planned series of events (real or imagined) that include specifications as to the various scenes and situations, the cast of characters and detailed direction for the stage setting and the development of the events."*

In the review of maritime OR projects, it was observed that the scenarios were used in 10 separate projects. This makes the FPS one of the most frequently used OR tools. The scenarios are of great importance especially because they are consistently used to put OR problems in context. For this reason, the review team recommended a closer examination of the use of scenarios in OR studies and if necessary, research into the related issues.

The following chapter will examine the particular projects that used FPS to extract commonalities and give directions for further research.

Force Planning Scenarios for Maritime OR Projects

The Force Planning Scenarios were used in the following 10 projects.

1. Signature Study for Frigates, Allen 2004.
   The goal of this study is to provide advice to upgrade electronic sensory measures (ESM) aboard frigates. Scenarios are used to build realistic simulations in SADM.

2. CMF 2015, Burton & al., 1998-1999.
   5 scenarios were developed for this study. They later became a part of the official FPS. The scenarios were used as input to the fleet scheduling model FleetSim. The frequency of occurrence of the scenarios was estimated from historical data.

3. Support to Force Structure/Defence Review '04-'05, Burton & al., 2003.
   In this combat task group effectiveness study the FPSs and the task group effectiveness model MARVIN were used to evaluate the effectiveness of certain sets of assets.

4. ALSC Options Analysis, Dore & Allen, 2003.
   The scenarios are used to extract required capabilities against which different options for the new ALSC are tested. The probability of occurrence of scenarios was used to give a weight to the different required capabilities. The frequency of occurrence of the scenarios was estimated from historical data

5. ALSC Logistics Over the Shore, Reding, 2001.

The study examined the probability that a logistics-over-the-shore (LOTS) would be required in future CF missions.

6. C4ISR Use of Space for Maritime Surveillance, Reding & Mitchell, 2001.
   This study used scenarios to determine the kind of coverage required by the navy. The study developed 6 scenarios based on FPS and attempted to find the best mix of sensors to maximize coverage of areas of interest as defined by these 6 scenarios.

7. Tyche Development, Burton, 2003.
   This study employed scenarios to generate random missions and then optimize the response to these missions based on a given set of available capabilities or assets.

8. Common MOPs and MOEs for ISR Systems, Fong, 2003.
   This was a multi-criteria analysis based study where different MOE's and MOP's were compared against different force planning scenarios.

9. HFSWR – Operational Evaluation II, Dore & Fong, 2002.
   This study looked at the impact of HFSWR on maritime control system in the context of different scenarios.

In all studies, scenarios are used to put a problem in context in a more or less formal manner. In a large number of studies, the scenarios are a framework for more precise analysis and the relative importance of the different scenarios is often a required measure.

Because it is not the purpose of the FPS to indicate anticipated potential future conflicts, an estimation of the frequency of occurrence of scenarios has deliberately been left out during the development of the FPS. However, looking at the different projects that used FPS, we can see that such a measure is necessary to make accurate predictions and is often calculated by the analysts with the best information available.

We will present here some possible directions for giving weights to scenarios to represent their relative "importance" within the context of an OR study. The difficulty of course lies in the definition of the importance of a scenario. The lack of a general repository for information related to the scenarios is another issue and will be discussed below.

Weighting Scenarios – The Risk Analysis Approach

As mentioned previously, the problem of determining the relative importance of the scenarios is a recurring one. Many studies have had to give weights to scenarios, usually using historical data and a qualitative assessment of potential scenario consequences. We will attempt here to formalize the process of attributing weights to scenarios, using a risk analysis approach. The following section will give a different approach, from multi-criteria decision analysis.

First, as suggested by Allen, Reference [9], and according to the standard definition of risk, let's define the weight of a scenario as the product of its probability of occurrence and the impact of negative consequences that could result from its occurrence. Many studies require only the frequency of occurrence but for multi-criteria decision problem, the product of the two measures is required. The first measure should obviously be independent of the study and all analysts should use the same probability values. The second measure could maybe be independent of the study as well, this will be discussed below.

Probability of Occurrence

Historical Data

The most straightforward method of predicting the frequency of occurrence of scenarios is to look at past data and assume that the past frequency is representative of the future. This poses a few problems, especially with scenarios that have not occurred in the past. Also, past changes in the CF operations render older data unusable. This is further complicated by the fact that, technically, the past data should cover a period that is at least as long as the period of interest for predictions. Above all, the major concern with this method is that there is no indication that past conflicts are representative of future ones. For lack of a better method, the projection of historical data is the current standard to calculate scenario frequency estimates in Maritime OR studies, Reference [70-73].

Empirical Bayes Data Analysis

Empirical Bayes (EB) inference, Reference [76], could be used to make better predictions for the frequency of occurrence of each scenario. EB looks at the historical data to build estimates for the parameters of the prior distribution. In other words, no prior distribution needs to be provided like in the case of parametric Bayesian methods. The predictions using EB have often been shown to give better results than other predictors. In particular, EB will give good results when an effect of regression towards the mean is expected. Further study should determine if such conditions describe the occurrences of different scenarios in time.

In the end, the prediction with Empirical Bayes inference may be better than with a linear projection of historical frequencies but the problem remains that future involvements depend on the geo-political situation and the CF policy (among other things). For example, the spectrum of involvements may become very different if the CF becomes focused on peacekeeping missions.

Input from Experts

Issues raised with the previous two methods of prediction indicate that part of the problem comes from a possible lack of correlation between past missions and future ones. This could be in part addressed by including strategic/policy analysts in the process of assigning weights to the scenarios. Experts could be surveyed for their opinion on the probability of occurrence of different types of conflicts in which the CF are susceptible to participate. This would become a consensus ranking problem.

It is not expected that OR analysts go through this process at every new study but rather that the priorities be established and provided to analysts as a tool to use in their studies. This relates to the question of the general information repository discussed later.

Dempster-Shafer Theory of Evidence

The theory developed by Dempster and later by Shafer is an extension of Bayesian theory, References [77-79]. It defines a set of rules and operators for combining evidence under uncertainty. It could be applied to combine evidence from past missions and evidence gathered from strategic analysts. This type of paradigm is typically applied to data fusion problem in ISR but has been extended to decision problems as well. This is a longer term project though and is not likely to produce good results immediately.

Measure of Negative Consequences

Many OR projects using scenarios were concerned with comparing the performance of a set of alternatives against different scenarios. In those studies, the relative importance of the scenarios needs to be established in order to get an overall ranking of the alternatives. With this risk analysis approach, we consider that the importance of a scenario depends on the probability of its occurrence and on the potential negative consequences that it could trigger. This second measure is subjective and is hard to establish. It would be convenient to have a scale against which poor performance can be measured, for all studies.

As suggested in Reference [20], the performance could be measured as mission success, personnel losses, materiel losses and impact on the CF reputation. A global performance level could be derived as a function of these (or other) 'performance meters'. Again, it is hard to come up with numbers to establish, for example, the difference in material losses between a 'bad' performance and a 'very bad' performance. The objective would not be to find the right number but rather to create a re-usable measurement scale.

Weighting Scenarios – The Multi-Criteria Decision Analysis Approach

A different approach to the scenario weighting problem is to consider the relative importance of a scenario as a combination of different criteria rather than as a measure of probability and impact. This would give a better idea of what is meant by 'importance'.

By ranking all of the scenarios for each of these 'importance' criteria, we transform the problem into a multi-criteria decision one. An overall ranking of the scenarios could be produced with MARCUS or any other multi-criteria decision analysis tool. Alternatively, the scenarios could be ranked based on their impact on overall defence goals and/or tasks.

The next step would be to assign scores or weights to the scenarios respecting this overall ranking. There is no perfect solution to this. Those scores could be derived informally or using a method like AHP, making sure that the final ranking is always respected.

This process could be repeated for every study to involve the client in the definition of the importance criteria and in the attribution of the final score. This makes sense if we assume that the relative importance of scenarios depends on the object of the study. However it doesn't solve the problem mentioned earlier, namely that similar work will need to be repeated for every study.

Another solution would be to go through this process once, with a mix of military experts, policy and strategy analysts and OR analysts to derive a weighting that will be used for all studies.

General Repository for Scenarios and Vignettes

The detailed description of the 11 departmental Force Planning Scenarios can be found on the DGSP web site, Reference[13]. However, to limit the duplication of work in OR projects using scenarios, it is recommended that a repository be created to store other related information.

This repository should contain the following.

a) The prioritized list of scenarios, with the frequency of occurrence established by whichever method was chosen. Those frequencies should be updated regularly.

b) The vignettes developed for particular studies. The only danger here is that the vignettes replace the original scenarios, and that the generality of the scenarios be lost.

Annex C: Decision Support and Statistical Advice

Introduction

Decision support methods include multi-criteria decision analysis and consensus ranking methods as well as other consistent decision support systems designed for a particular study. We exclude cost-benefit analysis and leave it for another chapter in this review emphasizing the issues related to costing. In our review of Maritime OR projects, we observed decision support methods in five separate projects. Following this observation and given the importance of such problems, the review team recommended that a survey of available methods and tools be carried out along with a discussion of their applicability and suitability.

The section will introduce the particular maritime OR projects that required some decision support. This will serve to define the general aspect of maritime OR decision problems and the requirements for new methods. We then present an overview of existing methods and tools that can be of interest, as well as some general recommendations on the use of decision support methods.

Review of the use of Decision Support for Maritime OR

The five Maritime OR projects from Phase One of the Maritime Review using decision support are the following:

1. ALSC Options Analysis, Dore & Allen, 2001:

   The object of this study was to determine the most appropriate option for the new Afloat Logistics and Sealift Capability (ALSC). Three methods were used, one of which consisted in using the algorithm based on the tau-x rank correlation coefficient to compare 7 option sets against a set of required capabilities derived from interviews with Subject Matter Experts (SME) and from the departmental force planning scenarios. This particular study uncovered the problem of tie handling with tau-x.

2. CMF 2015, Burton & al., 1998-1999:

   This study is part of an on-going effort to study options for the maritime force structure. In this case, the tau-x algorithm was used to compile the results of interviews with SME's.

3. Common MOE's and MOP's for ISR, Fong, 2003:

   This study was also a multi-criteria analysis with the tau-x method. Different MOE's and MOP's were compared against different force planning scenarios.

4. NATO Maritime Operations 2015, Saunders, 1998-2000:

One part of this study required a commercial decision support system to arrive to a consensus in a group of experts trying to determine plausible future maritime operations for NATO.

5. Integrated Undersea Surveillance System (IUSS), Way Ahead, Smith, 1999:

The core of this study was a cost-benefit analysis of different surveillance options but the author also developed a decision support system called Probability Impact Grids to combine the assessment of risk and benefits of different surveillance options. Assessments of risks and benefits were collected from different stakeholders in the IUSS project.

From those five projects, it appears that the decision analysis problems are mostly of three types:

a) Multi-criteria decision analysis: Evaluation of the performance of various alternatives on different criteria to determine the best alternative.

b) Consensus ranking: Collection of expert opinions on a set of alternatives and aggregation of the results to try to find a consensus.

c) Analysis of Simulation Results: Simulation of scenarios with discrete event simulation software to determine the parameters that produce the preferred outcomes.

Multi-Criteria Decision Analysis

Multi-Criteria Decision Analysis consists in assessing the performance of a set of options relative to a set of criteria and to determine the best overall option. The performance of options can be absolute (score, grade) or relative (ranks).

The tool most commonly used for Multi-Criteria Decision Analysis in maritime OR projects was the method based on the tau-x rank correlation coefficient, developed by Emond and Mason, Reference [66]. This method has proved useful for many studies but showed weaknesses for the ALSC options analysis. The problem was addressed and the improved method, called MARCUS, can now deal with multi-criteria analysis problems with weak and strong ties and can be used for consensus ranking problems as well. A description of the improvements to this method can be found in, Reference [28].

MARCUS works well for multi-criteria problems, especially when the preference between options is expressed as a ranking. However, in situations where the performance of the alternatives relative to the criteria is quantifiable and performance targets can be established for each criterion, it may be preferable to use a goal programming approach. For example, when comparing weapon systems based on effective firing range, accuracy and reaction time.

The goal programming approach consists in formulating the multi-criteria problem as a linear program with one constraint for each criterion and one variable for each option. Each constraint includes a variable representing the deviation from the target and the objective is to minimize the sum of the deviation variables. To use this approach, the problem only needs to be formulated in the goal programming manner, Reference [29], in LINDO or MATLAB and can be solved by any linear program solver. It would be a simple task to create an interface for this type of method.

Many commercial tools are also available for multi-criteria decision support. Details are given below for a few of them. Further research could determine if any one of them could provide some improvement to our current tools. At first sight, it appears that those packages do not provide better algorithms or methods but have convenient interfaces that allow easier input of data and exploration of the output. Those packages also provide sensitivity analysis features that allow the user to explore the decision space. We currently do not have sensibility analysis features on any software other that the Lagrange multipliers on commercial solvers like LINDO and MATLAB.

It is recommended that MARCUS continue to be used for most multi-criteria analysis problem and consensus ranking problems, with particular attention to the problem formulation with weak and strong ties. The only exception being problems where the performance of options is quantifiable (ex: firing range) and targets can be established for each criterion (ex: minimum firing range).

Research could also determine if the two approaches could be combined when the criteria are not all quantifiable.

Consensus Ranking

Given *n* options and *m* rankings, the consensus ranking problem consists of finding the ranking that best represents the consensus opinion. A ranking is an ordered list of options with possible ties and missing values, rankings can also have weights.

Typical consensus ranking problems arise when a group of experts are asked their opinion on a set of alternatives. The results need to be aggregated to determine what ordering of alternatives represents the consensus opinion.

As mentioned previously, the MARCUS software can handle consensus ranking. The user must take care to enter the appropriate types of ties, Reference [28], for the correct usage.

Other commercial software exist for consensus building like Equity, Reference [80, their most interesting features are the graphical interface and the technological possibilities to facilitate data collection in real-time from large groups of rankers. Based on the survey of maritime OR projects, it appears that this feature has not been required. Therefore the use of MARCUS should suffice.

Behavioural Considerations

In a few of the maritime OR projects involving consensus ranking, expert opinions were sought through interviews and questionnaires. Although we have not studied with attention the questionnaires themselves or reviewed the interviews, it is of interest to note the possible biases that can be introduced by behavioural considerations. In, Reference [3], many examples are provided to enforce the idea that cognitive biases like anchoring can severely impact the results of a study. Anchoring in particular can easily be avoided when the analyst designing the question set is aware of it. Another significant behavioural consideration that should not be overlooked is the fact that mechanical errors increase greatly when the process is long and/or arduous, Reference [31]. This is especially true when using software that apply the Analytic Hierarchy Process (AHP) where a lot of pairwise comparisons are required. Lapses in the user's attention can cause enough mistakes to render the results of the analysis false.

Further research in this area could result in guidelines for writing questionnaires and conducting SME interviews.

Analysis of Simulation Results

The third type of decision problem identified was related to simulations. Often, the analyst needs to run a simulation many times with different sets of parameter values to try to get a global understanding of the system being studied. The choice of the best parameter values is then achieved through trial and error and with some level of intuition.

Current research, Reference [32], is looking at combining discrete event simulation (like MARVIN or any ARENA model) with multi-objective evolutionary optimization such as Genetic Algorithms to reduce the space of parameters to explore. A Mine Counter Detection Measures (MCDM) system could provide the choice for the preferred solution from this reduced set of outcomes and provide a strategy for improvement (a new search direction). This iterative decision support system would be interactive.

Some of these ideas have been applied to chemical process design using a commercial numerical simulator and an interactive multi-objective optimization method called NIMBUS, Reference [33].

Overview of Multi-Criteria Decision Support Tools

Decision analysis problems do not always require software support. A sound analysis tailored to a particular problem is sometimes enough. The main advantages of computer packages are the possibility to easily modify the input and the informative presentation of the output.

The following is a short description of the main commercial software tools for decision support. Most of these products are based on either the Analytic Hierarchy

Process or Multi-attribute Utility Theory (MAUT) or sometimes even a combination of both. The Analytic Hierarchy Process, developed by Saaty, Reference [81], is characterized by its procedures for deriving weights and scores based on pairwise comparisons between criteria and between options. The Multi-attribute utility theory is based on the method developed by Keeney and Raiffa, References [82-83], and relies on the determination of a utility function to express the performance of options relative to the criteria. Those two methods are among the most frequently used analysis techniques for multi-criteria decision problem.

A demo version of most of these products can be found on their websites, Reference s[84-87].

ExpertChoice (AHP)

ExpertChoice® is based on the Analytic Hierarchy Process (AHP); it was one of the first decision support software developed. It consists of an interface to help structure the model and apply pairwise comparisons to determine the weight of criteria and options. The weighting can be done qualitatively, numerically or graphically. The options can be rated with different schemes, like ratings or utility curves. Dynamic sensitivity graphs permit the exploration of the results.

HiView

HiView® is a windows software based on multi-attribute utility theory. The product is marketed by Catalyze and Entreprise LSE, UK. It was originally developed to facilitate decision conferencing and is still one of the best software available for that purpose. The user can visually create and edit the value tree representing the hierarchy of criteria. The input and output interface is simple and the sensitivity analysis is good compared to other software. The latest version includes the MACBETH method for qualitative pairwise comparisons. HiView can solve large and complex multi criteria decision analysis problems.

MACBETH

The MACBETH method converts possibly incomplete qualitative judgments about the difference in attractiveness of pairs of options into numerical scores. The same approach can be used to determine criteria weights. The MACBETH method is implemented in the software "MACBETH® for multi criteria decision analaysis.

Equity

Equity® is marketed by Catalyze like HiView. While HiView is oriented towards multi-criteria decision analysis and decision conferencing, Equity's focus is cost-benefit analysis. The mathematical treatment is similar to HiView but the weighting schemes are more complex. See Reference [34] for a more complete description of the two software and their differences.

VISA (Visual Interactive Sensitivity Analysis)

VISA® is a Windows software similar to HiView. The main feature of VISA is the interactivity of some graphs in the sensitivity analysis. This allows the user to make modifications to the input and visualize the changes in the output. VISA can handle quantitative and qualitative attributes. This is considered to be more of an academic software and features are regularly added to the prototype as academic research progresses.

DESYSION DESKTOP

Also a Windows software, DECYSION DESKTOP is directed to decision makers rather than analysts. This is a step-by-step procedure to formulate the decision problem, assign weights, priorities, perform the analysis and explore the results. The output is displayed graphically and numerically and the sensitivity analysis allows the user to compare alternatives individually and modify the input. The results can be saved but there is no report writing functionality like in most other software.

Hipre3+

Originally Hipre3+ was a DOS based program that combined features of AHP and multi-attribute utility theory. There is now a web version called Web-Hipre, Reference [35], that is freely accessible on the internet. Unfortunately there is no file transfer possibilities so all data must be entered manually or by cutting and pasting. The distinguishing feature is that it allows multiple value trees. The sensitivity analysis is rudimentary.

Logical Decisions

Logical Decisions is also a hybrid of MAUT and AHP. It uses a different terminology than the other software, which can be confusing, and the display if not good for large value trees. Its characterizing feature is that is allows the input of random data.

Interactive Decision Support (IDS)

IDS is a different type of software, it allows the input of interval data and degrees of belief (uncertainty) in the decision matrix. This feature is based on the Evidential Reasoning approach, an application of Dempster-Shafer theory of evidence. Like most of the other software, it has good sensitivity analysis features.

Outranking methods: ELECTRE, PROMETHEE and SMART

From the ‘French’ school, opposed to the AHP approach. Those methods essentially consist in asking the decision maker to rank the options, the method then tries to find the options or groups of options that are ‘dominated’ by others. The result is a partial ordering of the options. Those methods are the ones that resemble the most MARCUS.

More information on these software and methods can be found in Reference [36]. A survey of some multi-criteria analysis software can also be found in, Reference [37]. Note, also, that "OR/MS Today" publishes an annual survey of decision analysis software, Reference [67].

Summary

It is recommended that the MARCUS software continue to be used for Multi-Criteria Decision Analysis and Ranking Consensus Problems wherever rank ordering is appropriate and that users familiarize themselves with the new concept of weak ties and strong ties. For quantifiable objectives and performance it is recommended to use a goal programming approach. Also, it is recommended that a better interface be developed for MARCUS, especially for multi-criteria analysis. An interface could also easily and quickly be written to facilitate the use of goal programming in MATLAB.

The survey of decision support tools presented here is fairly general; a more detailed survey should be conducted if any of these tools were to be acquired. A 'best practice' guide could be written to help in the design of questionnaires and interviews for SME's. Furthermore, research into the integration of event-based simulations with decision support could have repercussions on a wider range of OR problems and improve our use of discrete simulations.

Finally, further research could also determine if it is possible to combine MARCUS and the goal programming approach. This would make more versatile software for complex multi-criteria decision problems.

Annex D: Intelligence Surveillance and Reconnaissance Modelling

Introduction

When we discuss the ISR projects documented in the Maritime Operational Research Toolset Review Phase I (Reference 2), we should be clear that most of these projects emphasise surveillance and to a lesser degree reconnaissance. The intelligence component of these studies has been, in general, quite limited.

A limited survey of selected current activities and models in use within Canada and by our allies has highlighted three models of particular interest. These are documented below.

SIMLAB

SIMLAB is a physics-based simulation software package developed by DRDC Ottawa. It is designed to model C^4ISR scenarios and can simulate multiple surveillance sensors and targets, and model data flow from detection to data fusion.

Since the submission of the Maritime Operational Research Toolset Review Phase I (Reference 2) for publication, significant progress has been demonstrated (Reference 15) in the use of SIMLAB within the CORA, in conjunction with a traffic generation model created by DASOR known as MATRICS. The example scenario of Reference 15 models, or is intended to model, the High-Frequency Surface Wave Radar (HFSWR) system, Uninhabited Airborne Vehicles, RADARSAT, Maritime Patrol Aircraft and the Automatic Identification System. The work presented in this shows very impressive results in the area of data fusion and ISR modelling. It is the view of this author that this work is of considerable value to ISR modelling within CORA and that the work of V. Fong should be continued[5], despite the steep learning curve associated with the package.

SURPASS

SURPASS is an event-driven stochastic simulation model developed for the Royal Netherlands Navy by the TNO Physics and Electronics Laboratory (References 16 and 17). Its name is an acronym for **SUR**face **P**icture **ASS**essment. It models the process of maritime surface surveillance or surface picture compilation in an area with several types of shipping. Ten classes of surface vessels are modelled. At the time of writing of Reference 17, the primary surveillance assets modelled in SURPASS are frigates, helicopters and Maritime Patrol Aircraft. Sensor systems modelled include radar, infrared, visual, electronic support measures and sonobuoys. Detection is handled in a cookie-cutter fashion, modified by the ship type, altitudes and time of day.

[5] Dr. Fong has since been posted to another OR team.

Measures of Effectiveness, which are continuously calculated and updated by the model, include the Recognised Surface Picture quality, both momentary and averaged over the simulation period and the fraction of ships having ever been assigned a positive identity both overall and per type of ship.

The objective of the model is to provide insight into the means required for surface picture compilation and the way to deploy these means, in essence searching for solutions to the Online Travelling Salesman Problem for a given scenario.

From the point of view of the author, and in terms of its applicability to Canadian ISR problems, SURPASS has several significant shortcomings:

a. the communication between surveillance units is perfect. Each unit is able to see and use the information of any other unit;

b. the determination of the position of a contact is done without errors;

c. the breadth of ISR platforms modelled appears to be too narrow for Canadian purposes. In particular, it is far from clear how to handle the HFSWR system or RADARSAT; and,

d. finally, from the documentation available at the time of writing, the data fusion techniques used within SURPASS are not apparent. Given the central nature of the data fusion problem to the Recognised Maritime Picture, this aspect would require more investigation before SURPASS could be used in a Canadian context.

MANA

The Command-and-Control and Situational Awareness modelling built into MANA may have some applicability to ISR modelling. See Annex A for more information on MANA.

Conclusion

Based on the preliminary examination performed, SURPASS does not appear to possess sufficient capabilities beyond the CORA's current set of ISR models to warrant its acquisition.

Recent work using SIMLAB has shown great promise and should be continued. Resources may need to be devoted to the development and maintenance of proficiency in the SIMLAB model.

The New Zealand model MANA may also be of use to some categories of ISR problem. Further investigation is planned.

Annex E: Costing Analysis and Cost Models

Background

Phase 1 of the Maritime Tool Set Review, Reference [1, 2] identified costing analysis and cost models as an integral part of force structure studies as well as the acquisition process for military systems of all types. However, the review found little evidence that any of the Maritime Operational Research Teams are providing costing analysis as part of their operations research studies and no specific cost estimation models were observed. Although cost figures do appear in some studies, these are typically summary values provided by the study sponsors and not analyzed in any detail in the study report. Therefore, Part 3 of Phase 2 of the Maritime Tool Set Review was to focus on costing analysis and cost models.

Costing Analysis and Cost Models

The following section will begin with a review of the standard resources available in the department for cost analysis:

a. The Assistant Deputy Minister (Finance and Corporate Services) Costing Handbook, Reference [47];

b. The Assistant Deputy Minister (Material) Life Cycle Costs Guidance Manual, Reference [48]; and

c. The Vice Chief of Defence Staff Defence Management System Manual, Reference [49].

Then three specific cost models will be discussed and the potential of integrating these models with existing maritime effectiveness models will be determined.

The Costing Handbook

The Directorate of Costing Services produced a costing handbook in December 1994 and it is available on the Defence Wide-Area Network. It contains a large number of definitions of economics terminology such as ‘constant year dollars’, ‘budget year dollars’, ‘discounted cash flow’, ‘pay back period’, ‘rate of return on investment’, etc. It also lists a large number of data sources such as the Personnel Management Information System, the Aircraft Maintenance Management Information System, the Construction Engineering Management Information System, the Financial Information System, with a description for the reports that can be obtained, limitations with the information contained, and a contact. It describes various methods of cost estimation such as the bottom-up engineering approach, the parametric approach, the analogy approach and the expert opinion approach. It even gets into such things as sensitivity analysis and how to present findings. The Costing Handbook is very much oriented towards Business Case Analysis. It provides a detailed step-by-step process for conducting a Business Case Analysis. Business Case Analysis is primarily about finding cost savings through improved processes. It takes a current process as the baseline and based on accounting principles attempts to determine the cost of conducting the process in the current manner. It then considers viable alternative ways to complete the same process and estimates their benefits, costs and risks to select the best option and plan its implementation.

Although there is nothing particularly incorrect about Business Case Analysis, there is also nothing particularly novel about it (we can consider it roughly equivalent to the cost-effectiveness analysis commonly promoted by OR analysts). It may have been so closely associated with the cost-cutting measures in the department during this period of time that it never really caught on with our military clients. It should be the job of the OR personnel to ensure that effectiveness and capabilities analysis are not being given a 'short shrift' in this methodology and are considered equally with cost analysis.

The Life Cycle Costs Guidance Manual

The author was involved in the writing of this manual in the early 1990's and a number of the references in the document seem quite dated today. There is a great deal of overlap in the discussion in this manual and the costing handbook. They both define the concepts of engineering bottom-up estimation, parametric estimation and analogy estimation. They describe dollar types, inflation and discounting, data sources and suggest ways to conduct sensitivity analysis and present results.

Some other information provided in the Manual are a discussion of cost breakdown structures and three computer models (PRICE, CASA, and LOGAN) that can be used for cost estimation. Each of these models will be discussed in more detail below. The Manual includes three case studies.

The major complaint about Life Cycle Cost-Effectiveness using these computer programs is that it assumes that effectiveness can only be measured by 'operational availability' when most military decision makers wish to determine effectiveness using many measures of performance. Again it is up to the OR personnel to ensure that all the important measures of effectiveness are considered. Therefore, we will later recommend that these cost models be linked to the effectiveness models that have been developed by the maritime operational research community to obtain a balanced view of both effectiveness and cost issues.

The Defence Management System Manual

Chapter 9, Part 2 of the Defence Management System Manual is entitled "Costing a Proposal". It is a brief policy document that again summarizes dollar types and inflation factors. It also mentions classes of cost estimates, contingency costs and ammunition, and under a short section on Logistics Support it mentions Life Cycle Costing, the Life Cycle Cost Manual and the LOGAN computer model.

Therefore, we can see that Life Cycle Costing and particularly the PS Analyzer (LOGAN) computer model have some policy support behind them.

The Life Cycle Cost Module of the PS Analyzer Model

PS Analyzer was developed in Canada through a privatization program of the LOGAN model developed by the Directorate of Logistics Analysis in the Operational Research Division during the 1990's. Being a Canadian product, it is particularly popular for the Department of National Defence (DND) and has a fair amount of policy weight behind its use.

The PS Analyzer Model contains three modules: Spares Analysis, Life Cycle Cost Analysis, and Level of Repair Analysis. We will concentrate on the Life Cycle Cost module, however, the data input for the Life Cycle Cost module is an extension of the data input and model output of the other modules.

Data Input

PS Analyzer is intended for use during the acquisition process to support Logistics Support Analysis studies. This generally involves tradeoffs concerning equipment reliability and maintenance concepts. In particular, the determination of the 'optimal' distribution of spare parts to maintain the operational availability at a minimum cost is central to PS Analyzer. To do this, the user needs to input the equipment configuration in terms of assemblies, sub-assemblies, etc. each with estimates of their mean time between failure and turn around time. The user also must input the operational demands in terms of the location of the operating units and their support bases as well as the number of hours that the equipment will be required to operate in peacetime at these facilities.

Output Values

The output from the model involves the non-recurring costs such as research and development, acquisition costs, initial spare parts, facilities construction, purchase of test equipment and other setup costs. Then there are the recurring costs such as operating costs, regular and corrective maintenance costs, disposable spare parts and consumables, overhead costs such as operating facilities, etc. Finally, one might wish to consider the cost of disposal of the equipment at the end of its life.

Integration Issues

Two problems can be foreseen with the use of PS Analyzer in conjunction with the effectiveness models currently in use in the maritime operational research teams. First, the maritime operational research teams do not have the detailed data necessary to support the model because they are often looking at future systems that have not reached the state of mature design required. Second, the linking of the effectiveness models to the PS Analyzer model would be problematic because of the nature of the effectiveness measure (i.e. operational availability) linkage to cost (i.e. operating and support recurring costs) is not related to the parameters that might like to be manipulated by the maritime operational research teams in their trade off studies.

The CASA Model

The Cost Analysis Strategic Assessment (CASA) model was developed by the Defense Systems Management College for the US Department of Defense. It is promoted by them as the most widely used life cycle cost model in the world and is free to download from the CASA Home Page, Reference [50].

In terms of data input, it is similar to the PS Analyzer and requires a great deal of detailed data of the equipment. And in terms of the output, the primary measure of performance is operational availability. One of the interesting features of CASA is its ability to handle uncertainty in the inputs using Monte Carlo simulation.

It would appear that CASA would have the same difficulties integrating with the maritime operational research models as we have previously described in PS Analyzer.

The PRICE Model

The PRICE Model on the other hand is a parametric model that utilizes statistical cost estimating relationships. It looks to have great potential for integration with the maritime operational research models. In fact, Phoenix-Integration Inc. has already integrated PRICE with other effectiveness models to support trade off studies for designs of future systems, Reference [51].

The data input to PRICE is highly generic and should be available in the concept development stages of systems analysis. The outputs from PRICE are the standard measures of life cycle costs.

We recommend that the PRICE model be considered for the type of integration of cost and effectiveness that we are proposing for a ‘balanced’ view of the issues involved in maritime operational research studies of future systems and capabilities.

Bringing It All Together - Life Cycle Cost Effectiveness Analysis

This section will assume that effectiveness has many dimensions that can be quantified by various models that have been developed by the Maritime Operational Research Teams. We will consider various methods of linking cost to these effectiveness measures. Then putting these two analysis techniques together, it may be possible to conduct a life cycle cost effectiveness analysis.

Exploration Using Effectiveness Models

In the Phase 1 report, Reference [1], we have discussed a number of the Maritime Operational Research models that are in use by the Maritime Operational Research Teams. Like any computer software, they take input parameters and produce output. The problem of integration of these models into a complete maritime operational picture was discussed in the Phase 1 Strategic Perspective report, Reference [2]. The use of the High Level Architecture (HLA) promoted by the Department of Defense in the United States has been adopted by many nations including Canada for use in the integration of these ‘federates’ into ‘federations’. There is a problem with legacy models like those used by the Maritime Operational Research Teams that making these models HLA compatible involves a major overhaul of the code and becomes extremely expensive.

There is an alternative commercially available technology that allows legacy models to be ‘wrapped’ so that they can be considered as ‘black boxes’ and interconnected with other models and other types of software, Reference [52]. This commercially available software is already being used effectively in computer aided design projects for Boeing and Lockheed-Martin.

Along with this wrapping and integration capability, there are commercially available grid computing capabilities to speed up the processing of sensitivity analysis by using parallel computing, Reference [53] some of which is already being trialled in CORA.

Finally, these commercially available software have quite sophisticated graphical capabilities to display the results of many runs in many dimensions simultaneously, Reference [54]. Therefore, it would appear that many of the requirements of multi-dimensional effectiveness analysis can be met.

Integration of Life Cycle Costing Models

In the Phase 1 study, Reference [2], we recommended that work begin to integrate the individual effectiveness models into a common maritime simulated environment. With this integration, we will have a tool to examine tradeoffs with regards to many measures of effectiveness in maritime operations. However, we now propose that these effectiveness models also be integrated with costing models such as PRICE to look at a global optimization of the most cost effective solutions to our maritime operational challenges, Reference [55].

Phoenix-Integration Inc. has demonstrated the capability to integrate many different legacy models together using their ‘wrapper’ technology, Reference [52]. They have also demonstrated how the PRICE life cycle cost model can be linked to these effectiveness models, Reference [51] and how their genetic algorithm software, Reference [52] and grid computers can be employed to do the types of sensitivity analysis that is necessary, Reference [53]. They also appear to have the sophisticated graphics capability that would be required to visualize the results of this sensitivity analysis, Reference [54].

The tools available from Phoenix-Integration and PRICE Systems should be investigated for life cycle cost effectiveness studies of future maritime capabilities.

Conclusions

The Phase 1 reports on the Maritime Tool Set listed seven deficiencies and gaps that would be addressed in Phase 2. In this annex, we attempted to address the deficiencies of not having cost models and not doing cost analysis in an integrated manner. It is appropriate at this time to draw the following conclusions:

a. Cost analysis and cost models are an essential component of the type of cost-effectiveness studies that will be required by the Navy in the future;

b. The costing models PS Analyzer and CASA would not be well suited for the types of studies to be conducted in the Maritime Operational Research Teams because they require too much detailed data on the system components that would not be available at the concept development stage.;

c. The PRICE model would be a viable approach to cost analysis because it is a parametric model that requires only generic information about the design of the system; and,

d. There is a need to integrate the effectiveness modeling with the costing models so that cost and effectiveness can be measured and compared for different levels of capability.

Annex F: Issues with Detailed Physical Models

Background

Part 4 of Phase 2 of the Maritime Tools Set Review, Reference [56], looked at maintenance and support of the detailed physical models used in Maritime Operational Research. The following annex emphasizes that these models should be looked at as 'repositories' of the best knowledge currently available on the subject. Two models in the Maritime Operational Research suite stand out; namely, ODIN for under-water warfare, and SADM for above-water warfare but also SIMLAB, ANSWER, POSEIDON, and MSSM may be considered important tools in the suite. The argument is that these models are more than merely replaceable tools in a toolkit. They should be considered an ever-growing knowledge repository that should be cherished and nourished with resource investment. In particular, we should exploit available technology to learn more about the qualities of these models through the detailed examination of their underlying assumptions. Furthermore, intuition about the workings of these models could enhance and facilitate the learning process of employees asked to master these models, increase their productivity and contribute to the knowledge base if conducted in a systematic manner.

Part 6 of Phase 2 of the Maritime Tool Set Review, Reference [56], looked at a number of broader issues in Maritime modelling and simulation. It is well known in Operational Research that our studies will be subject to question about their validity especially if they produce 'counter-intuitive' results. In this case, the sponsor will wish to know whether it is the model that we used that is incorrect or the intuition. If proper verification, validation and accreditation (VV&A) have been conducted beforehand a great deal of time can be saved after the results are produced. However, validation of a model or simulation must be based on experiment with real systems and many of our OR models are used to examine the potential of future systems and therefore by definition cannot be validated. Furthermore, we believe that VV&A is based on the engineering paradigm that models can be proven to be true depictions of reality whereas OR views models as simplified abstractions of the real situation. We will examine an alternative methodology well suited to the needs of OR called 'exploratory analysis' that might satisfy the needs of the modeling and simulation community about the usefulness and quality of OR models and simulations.

We have combined these Parts of Phase 2 into a common annex because both of these issues might be addressed by an exploratory analysis approach the details of which will be discussed in further depth.

We will discuss briefly VV&A and potential responses by CORA. That will lead into the next section on Exploratory Analysis that should enhance the credibility of the organization by using sophisticated technology and the latest scientific methods. A multi-year research design based on exploratory analysis may also be useful maintenance and training of Maritime OR scientists in their work on detailed physical models.

Verification, Validation and Accreditation

There has been great interest recently in Defence Research and Development Canada concerning modelling and simulation using detailed physical models and associated with this interest has come an effort to standardize the processes of VV&A. The following definitions should be noted from the DND VV&A Recommended Practices Guidelines, Reference [57]:

> a. Verification is the process of determining the accuracy of the implementation;
>
> b. Validation is the process of determining the accuracy of the model or simulation in relation to the 'real world'; and
>
> c. Accreditation follows the common practice of other nations when it states that the 'user' will be the final accreditation authority.

CORA sent the author to the VV&A course. This was a very informative course and the comprehensive package of slides and notes are available in the CORA library, Reference [58].

Verification involves the checking of the computer code used to program the mathematical (conceptual) model. It should be noted that this step is often not considered in the CORA Peer Review process. A list of tools and techniques primarily oriented to verification of software are given in the Recommended Practices Guidebook, Reference [57].

The author believes that validation can only be done using controlled experiments. Therefore, since many models in OR concern future systems and future operations, most models in OR are 'un-validatable'. It should be noted that even if parts of a model, such as a missile fly-out, are validated using tests or trials, this does not validate the model as a whole if it is simulating battlefield conditions, such as command and control under pressure and fatigue. Similarly, live war games can be useful but cannot be considered validation of the 'real world' conditions. That is not to say that these 'un-validatable' models are not useful. VV&A would seem to be an engineering paradigm whereas OR coming from a scientific background would suggest that expanding the knowledge base via successive approximation of 'the truth' is a more promising and realistic approach.

Accreditation may be the most 'thorny' of the steps in the VV&A process. The 'user' in OR terms is the sponsor or the client and in general OR as a consultation branch of DRDC believes as other client oriented organizations that 'the customer is always right'. If a client organization requests a study, it is common practice to allow the client to review the report prior to publication and some sub-organizations of CORA actually follow a formal approval process by the client. However, this can be contentious if the results produced by the CORA scientist are ‘counter-intuitive’ and/or do not support the position that the client may desire. As public servants and scientists who strive to be objective, we must ‘speak truth to power’. Allowing the client the final authority for accreditation of CORA models will undermine one of CORAs key strengths, that of scientific integrity, and is not an option that this study recommends.

There is a strong argument that VV&A is more involved than the standard Peer Review process of normal scientific publication. VV&A is a highly seductive paradigm. Who could argue with a client that would like to see the models used in their study verified and validated. However, as one could imagine, to do a VV&A properly can be expensive and time-consuming. Furthermore, we are users of many of the detailed physical models and not their developers. So it is not clear if we have primary responsibility to conduct the VV&A for these models. Another difficulty involves the models’ state of development. Many of these models are evolving and the appropriate time to conduct the VV&A may be subject to question.

We have noted that VV&A is an engineering (mostly software engineering) paradigm and begins with the assumption that computer models can be validated. The scientific assumption of iterative approximation or the OR assumption of minimal but necessary detail provide a much different starting point. We have also noted that because OR often needs to model future system designs our detailed physical models may not be validatable because there is no experimental data on these systems. Some authors have examined this issue in OR and have proposed the concept of Exploratory Analysis as an alternative to VV&A.

Exploratory Analysis

Steven Bankes, Reference [59], of the Rand Corporation developed the concept of Exploratory Analysis in 1993 in response to a paper written by James Hodges in the OR Forum in 1991 (“Six (or so) Things You Can Do With a Bad Model”) , Reference [60]. James Hodges drew the conclusion that OR models, in general, could not be validated because they could not be subjected to ‘real life’ experimentation. Bankes felt that not using computer models because they could not be validated would deprive OR analysts of a potentially useful tool. He proposed that models generally use the best assumptions about the ‘real world’ that are available at the time and it would be worthwhile to see how far these assumptions can take us without leading to an inconsistency.

He and his team demonstrated how Exploratory Analysis might work in a simple Weapons Mix problem, Reference [61]. Later his team made more specific recommendations regarding war-gaming, Reference [62, 63]. One of the problems that they addressed was the need for a research (experimental) design that would allow for statistically sound conclusions to be drawn but would not be computationally explosive.

The case for Exploratory Analysis can be summarized in the following three points. First, OR problems are getting more and more complex as the routine problems of the past are being automated out of existence. For most of these new complex problems, there is no model that can be validated experimentally. However, that does not relieve the pressure to solve the problems. Second, as Bankes has noted, not using models because they cannot be validated deprives analysts of potentially very valuable tools. Thus, the question becomes one of risks versus benefits of using an unvalidatable model. Third, by conducting a thorough analysis of the model using readily available computing power, one might reduce the risks to some degree via knowledge of the consequences of alternative assumptions.

Exploratory Analysis may be more commonly known as computational experiments. This is a growing field that is replacing the standard experimental laboratory with a synthetic environment of computer simulation. To respond to the issue of VV&A in this environment, Bankes suggests that the power of computation be used to conduct 'super' sensitivity analysis involving thousands to billions of computer experiments with a model. Again we should note that this is not validation but it would help to determine the quality of the model in terms of the parameters and sub-models that will affect the simulated results in the most significant ways. This would help to answer questions or highlight issues if counter-intuitive results were obtained from the model.

In the case of Maritime Operational Research, there are two models that stand out: ODIN a model developed by Qinetiq in the UK for under-water warfare and SADM a model developed by BAE Systems in Australia for above-water warfare. Both of these models are complex and have proven in the past to be useful. However, both models have also had their validity come under question because they have produced counter-intuitive results. Thus, Exploratory Analysis on these models might improve their credibility and improve our understanding of them. With an incremental research design that built up knowledge concerning these models, the learning curve might be reduced and the problem of transferring knowledge from one scientist to another might be alleviated.

One of the issues with the conduct of an Exploratory Analysis is that it would probably require a separate project. To try to conduct it using existing resources this would draw those resources away from currently important and immediate tasks for an extended period of time thereby threatening the viability of the current Maritime Operational Research program of work. This would be the first time that such as project was undertaken by CORA and there might be significant risk associated. However, if successful, much of the learning curve on how to conduct Exploratory Analysis for other CORA models would be achieved.

Besides people and time, the other resources that would be required would be investment in theoretical work on experimental design under these conditions. The Rand experience could be very useful here. Computational power would be required. Fortunately, this is relatively cheap, especially if grids of existing computers can be employed, as has been trialed in a recent study in CORA, Reference [74]. Good experimental techniques would be required and since millions of experimental simulation runs might be required an automated means to collect the experimental parameters and their associated results would be advantageous. Some authors have recommended automated search routines, such as genetic algorithms, for minimizing the number of runs required, Reference [64]. Also the visualization of multi-dimensional spaces would be required for interpretation of the results and would greatly enhance the analyst's intuitive grasp of the model. There is a possibility of developing many of these resources by employing sophisticated applications such as MATLAB or Mathemetica.

As we have noted these models should be considered repositories of our collective knowledge on these subjects. Exploratory Analysis can clarify and thereby add to this knowledge base. It is hoped that through visualization of the results of many runs under differing conditions, intuition can be gained that might help new employees learn these models more efficiently and thereby also reduce the burden to maintenance and training on the Maritime OR Teams.

Conclusions

A very large percentage of the maritime operational research work consists of the use of models and simulations such as ODIN, SADM, SIMLAB, ANSWER, POSEIDON, and MSSM. There is an active program to enhance the department's (and our allies') modeling and simulation capability by developing policy and procedures in the area of verification, validation and accreditation. However, trying to validate existing these OR models might end up being a total waste of time using the engineering oriented VV&A paradigm. Some authors in the literature question the benefits of attempting to validate OR models because they often are focused on future un-developed systems and procedures for which no experimental data is available. By using an OR paradigm like Exploratory Analysis which is a type of 'super' sensitivity analysis to learn more about our models, we might be able to qualify our results according to the assumptions that are used or suggest alternative assumptions and thereby preserve many of our OR models relatively intact and even improve a number of them in significant ways.

With regards to maintenance and training of our detailed physical models, we have approached this issue only indirectly. Intuitive understanding of the capabilities and limitations of these models might be enhanced by an Exploratory Analysis program of research. The use of a multi-year experimental research design might allow the building of a knowledge base that can be more easily transferred from one scientist to another.

Finally, we note that there is the capability to support the requirements of Exploratory Analysis with powerful grid computing, novel genetic algorithms and sophisticated multi-dimensional visualization tools through the resources provided by Phoenix-Integration.

List of symbols/abbreviations/acronyms/initialisms

AHP	Analytic Hierarchy Process
ALSC	Afloat Logistics and Sealift Capability
C4ISR	Command, Control, Communications, and Computers, Intelligence, Surveillance, and Reconaisance
CASA	Cost Analysis Strategic Assessment
CF	Canadian Forces
CFMWC	Canadian Forces Maritime Warfare Center
CMF	Canadian Maritime Forces
CMS	Chief of the Maritime Staff
CORA	Center of Operational Research and Analysis
CORT	Central Operational Research Team
D Mar Strat	Director of Maritime Strategy
DASOR	Director Air Staff OR Team
DND	Department of National Defence
DOS	dirty operation system
DRDC	Defense Research and Development Canada
EB	Empirical Bayes
EBM	equation-based models
EINSTein	Enhanced ISAAC Neural Simulation Tool
ESM	electronic sensory measures
FleetSim	Fleet Simulation
FPS	Force Planning Scenarios
HFSWR	High Frequency Surface Wave Radar
HLA	High Level Architecture
IDS	Interactive Decision Support
ISAAC	Irreducible Semi-Autonomous Adaptive Combat
ISR	Intelligence Surveillance and Reconaisance
IUSS	Integrated Undersea Surveillance System
MANA	Map Aware Non-uniform Automata
MARCUS	Multi-Criteria Analysis Ranking Consensus Unified Solution
MARLANT	Maritime Forces Atlantic
MARPAC	Maritime Forces Pacific
MARVIN	Maritime Vignette
MAUT	Multi-attribute Utility Theory
MCDM	Mine Counter Detection Measures
MOE	Measure of effectivenss
MOP	Measure of performance
MORT	Maritime Operational Research Team
NATO	North Atlantic Treaty Organization
NDHQ	National Defence Headquarters
OR	Operations Research
OR/MS	Operations Research/Management Science
SADM	Ship Air Defense Model

SME	subject matter experts
STK	Satellite Tool Kit
TTCP	The Technical Cooperation Panel
VISA	Visual Interactive Sensitivity Analysis
VV&A	verification, validation and accreditation

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1. Enclosed is the Centre for Operational Research and Analysis Technical Report TM 2005/xx, "Maritime Operational Research Tool Set Review – Final Report".

2. This report documents the findings of Phase 2 of the Maritime Operational Research Tool Set Review being conducted for the Centre for Operational Research and Analysis of the Canadian Department of National Defence. The report provides specific recommendations for each of six methodological areas identified as gaps in Phase I of the Maritime Operational Research Tool Set Review.

3. The six methodological areas are: Task Group Effectiveness Modelling, Use of Force Planning Scenarios, Decision Support and Statistical Advice, C4ISR Modelling, Costing Analysis and Cost Models, and Issues with Detailed Physical Models.

4. Questions or comments on the report may be directed to Mr. Edward J. Emond (613) 992-4730 or Mr. Paul Massel (613) 996-3898.

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This project report documents the findings of the Maritime Operational Research Tool Set Review carried out by the Central Operational Research Team as part of its mandate to stimulate intellectual renewal within the Operational Research Division of the Canadian Forces. Based on research carried out during Phase 2 of the Review, specific recommendations are given for each of six methodological areas identified as gaps or deficiencies in the maritime Operational Research tool set. The six methodological areas are listed below.

1. Task Group Effectiveness Modelling
2. Use of Force Planning Scenarios
3. Decision Support and Statistical Advice
4. C4ISR Modelling
5. Costing Analysis and Cost Models
6. Issues with Detailed Physical Models

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