Optimizing a System of Systems

Experience Using Phoenix-Integration Model Center in the CapDEM Beta Trial

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Abstract

The CapDEM Beta Trial was intended to test the Capability Engineering process using a study of the Surveillance and Reconnaissance of the Northwest Passage. The project began with series of briefings in NDHQ and DRDC Ottawa on 1-3 November 2005 and completed on 1 March 2006. The author was a member of the Investment Options Analysis Team and the following paper documents the use of the Phoenix-Integration Model Center in the optimization of the System of Systems options based on performance, cost, schedule and risk. A genetic algorithm called Darwin, available with the Model Center software, was found to be flexible and robust for this complex problem that involves a huge integer-based solution space and highly non-linear, discontinuous functional expressions for the objective and constraints. The author is confident that the Phoenix-Integration software will prove valuable in future real-life decision analyses.

Résumé

Les essais beta de DIGCap avaient pour objectif de tester le processus d'ingénierie de capacité en faisant appel à une étude sur la surveillance et la reconnaissance du passage du Nord-Ouest. Le projet a commencé par une série de rencontres au QGDN et à RDDC-Ottawa du 1er au 3 novembre 2005 et il s'est terminé le 1er mars 2006. L'auteur était membre de l'équipe d'analyse des options d'investissements et le document suivant présente l'utilisation de Model Center de Phoenix Integration en vue de l'optimisation des options de système de systèmes sur le plan des performances, des coûts, des échéanciers et des risques. L'algorithme génétique Darwin, disponible dans le logiciel Model Center, s'est révélé à la fois souple et robuste pour la résolution de ce problème complexe qui met en jeu un énorme espace de solution à base d'entiers et des expressions fonctionnelles extrêmement non linéaires et discontinues pour représenter les objectifs et les contraintes. L'auteur est persuadé que le logiciel de Phoenix Integration se révélera utile pour la prise de décision dans des cas réels.

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Executive summary

Optimizing a System of Systems

Ivan Taylor; DRDC Centre for Operational Research and Analysis TM 2007-19;
Defence R&D Canada – CORA; June 2007.

The CapDEM Beta Trial was intended to test the Capability Engineering process in a near real-life example but with a compressed time frame. The project began with a series of briefings in NDHQ and DRDC Ottawa on 1-3 November 2005. The Beta Trial completed the study of the Surveillance and Reconnaissance of the Northwest Passage on 1 March 2006. The author was a member of the Investment Options Analysis Team. The objective of the Investment Options Analysis was to provide value-added to the Capability Engineering process by analyzing the requirements, scenarios and systems data to produce a recommendation to senior decision-makers on a short-list of solutions to the capability gap that was acceptable in terms of the four dimensions of performance, cost, schedule and risk. With support from the Requirements, Operational Architecture and System of Systems (SoS) Architecture teams in the CapDEM Beta Trial, and using the Phoenix-Integration Model Center software, the Investment Options Analysis Team found that it was a relatively straightforward process to determine the optimal SoS solution to meet the performance requirements at minimum cost.

The Investment Options Analysis Team built submodels for performance, cost, schedule and risk based on data provided by the other teams. These models contained specialized internal logic and data parameters and were independent of each other except that they could be linked together by the Phoenix-Integration Model Center to examine the same SoS option. There were nine systems identified by the System of Systems Architecture Team which included: Maritime Patrol Aircraft, Unmanned Aerial Vehicles, Land Based Radars, Ranger Patrols, Satellites, Frigates, Icebreakers, Submarines, and Remotely Deployed Sonars. An SoS option might consist of 5 MPA, 6 UAV, 3 Frigates, and 3 Icebreakers employed in some particular configuration in 13 scenarios. This SoS option with its allocation to the scenarios would have certain performance, cost, schedule and risk characteristics that would be calculated by the submodels.

For the CapDEM Beta Trial and likely for future SoS optimization, Phoenix-Integration Model Center which comes with a genetic algorithm tool, called Darwin, could be used to optimize an appropriate objective function subject to constraints over a series of design parameters. We found this tool to be flexible and robust for SoS optimization compared to other optimization techniques that were available, such as the gradient method, because our design space consisted of integer values and the objective and constraint functions were highly non-linear and discontinuous.

In the past, Investment Option Analysis has been restricted to a limited number of specific options which are analyzed manually according to simple criteria and then these criteria are scored and weighted to compare the options. This approach is deficient in a number of respects not least that the weights and scores are usually based on subjective judgment that can have a significant impact on the recommendation. The approach that we took in the CapDEM Beta Trial was to model each of the dimensions of performance, cost, risk and schedule using objective data that provided an audit trail. In other words, we developed quantitative models using numerical estimates of the data and applied a rigorous process of analysis. Then we utilized the Phoenix-Integration Model Center to optimize over the solution space and thereby find an SoS option that provided the performance requirements at minimum cost. The search covered millions of potential options, not a limited set.

Future work will involve the application of this approach to a real decision process using more complex models of performance, cost, schedule and risk. The Investment Options Analysis Team believes that the Phoenix-Integration software is up to the task of integrating and optimizing these more complex models in a real decision process.

Sommaire

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Ivan Taylor; DRDC Centre for Operational Research and Analysis TM 2007-19; R & D pour la défense Canada – CARO; juin 2007.

Les essais beta de DIGCap avaient pour objectif de tester le processus d'ingénierie de capacité dans un cas très proche de la réalité, mais dans une période comprimée. Le projet a commencé par une série de rencontres au QGDN et à RDDC-Ottawa du 1er au 3 novembre 2005. Les essais beta ont mis fin à l'étude de surveillance et reconnaissance du passage du Nord-Ouest le 1er mars 2006. L'auteur était membre de l'équipe d'analyse des options d'investissements. L'objectif de l'analyse des options d'investissements était d'ajouter de la valeur au processus d'ingénierie de capacité en analysant les besoins, scénarios et données système afin d'élaborer une recommandation à l'intention des décideurs de la haute direction au sujet d'une liste restreinte de solutions visant à résoudre les lacunes sur le plan des capacités, solutions qui seraient acceptables sur le plan des performances, des coûts, des échéanciers et des risques. Avec le soutien des équipes Besoins, Architecture opérationnelle et Architecture de système de systèmes pour les essais beta de DIGCap, et en utilisant le logiciel Model Center de Phoenix Integration, l'équipe d'analyse des options d'investissements a trouvé que le processus permettant de déterminer quelle serait la solution optimale de système de systèmes répondant aux besoins de performance au plus bas prix était relativement simple.

L'équipe d'analyse des options d'investissements a élaboré des sous-modles pour les performances, les coûts, les échéanciers et les risques en se fondant sur des données fournies par d'autres équipes. Ces modèles contenaient de la logique interne et des paramètres de données spécialisés et ils étaient indépendants les uns des autres, sauf qu'ils pouvaient être reliés ensemble au moyen de Model Center de Phoenix Integration afin d'examiner une même option de système de systèmes. Neuf systèmes ont été examinés par l'équipe d'architecture du système de systèmes, c'est-à-dire aéronefs de patrouille maritimes (APATMAR), véhicules aériens téléguidés (VAT), radars terrestres, patrouilles de Rangers, satellites, frégates, brise-glace, sous-marins et systèmes sonar déployés à distance. Une option de système de systèmes serait composée de 5 APATMAR, 6 VAT, 3 frégates et 3 brise-glace employés dans diverses configurations particulières correspondant à 13 scénarios. Cette option de système de systèmes, en regard des scénarios, présente certaines caractéristiques sur le plan des performances, des coûts, des échéanciers et des risques qui seraient calculées par les sous-modèles.

Pour les essais beta de DIGCap et probablement pour l'optimisation éventuelle du système de systèmes, Model Center de Phoenix Integration, qui comporte un outil à algorithme génétique nommé Darwin, pourrait être utilisé afin d'optimiser une fonc-

tion objective appropriée soumise à des contraintes pour une série de paramètres de conception. Nous avons trouvé que cet outil est à la fois souple et robuste pour optimiser un système de systèmes comparativement à d'autres méthodes d'optimisation disponibles, comme l'analyse de gradient, car notre espace de conception se composait de valeurs entières et que l'objectif et les fonctions de contraintes étaient grandement non linéaires et discontinues.

Auparavant, l'analyse d'option d'investissement a été restreinte à un nombre limité d'options spécifiques qui ont été analysées manuellement en fonction de critères simples, puis ces critères étaient notés et pondérés afin de comparer les options. Cette approche présente plusieurs lacunes parmi lesquelles le fait que les pondérations et les notes sont habituellement basées sur un jugement subjectif n'est pas la moindre et elle peut avoir une incidence considérable sur la recommandation formulée. La démarche que nous avons adoptée lors des essais beta de DIGCap a consisté à modéliser les dimensions performance, coût, risque et échéancier en appliquant des données objectives qui ont permis d'obtenir une piste de vérification. En d'autres termes, nous avons développé des modèles quantitatifs au moyen d'estimations numériques des données et nous leur avons appliqué un processus d'analyse rigoureux. Nous avons ensuite utilisé Model Center de Phoenix Integration afin d'optimiser l'espace de solution et nous avons ainsi trouvé la solution de système de systèmes répondant aux besoins en matière de performance au plus faible coût. La recherche a ainsi porté sur des millions d'options possibles, et non sur un ensemble limité.

Les travaux à venir consisteront à appliquer les résultats de cette démarche à un processus de décision réel faisant appel à des modèles plus complexes de performance, coût, risque et échéancier. L'équipe d'analyse des options d'investissements croit que le logiciel de Phoenix-Integration est à la hauteur de la tâche qui consiste à intégrer et optimiser ces modèles plus complexes dans un processus de décision réel.

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1 Introduction

The CapDEM Beta Trial [1] was intended to test the Capability Engineering process in a near real-life example but with a compressed time frame. The project began with series of briefings in NDHQ and DRDC Ottawa on 1-3 November 2005. The Capability Engineering process [2] involves four phases: Inception, Comprehension, Elaboration, and Completion. A spiral analysis methodology is utilized in which a capability gap is examined, solutions to fill the gap are analyzed, and a final short list of solution options are recommended to senior decision-makers. The Beta Trial completed all four stages of this process for the study of the Surveillance and Reconnaissance of the Northwest Passage on 1 March 2006.

Capability Engineering is conducted by four interrelated teams of analysts [3]. The author was a member of the Investment Options Analysis Team in the CapDEM Beta Trial, thus the description of the other teams' functions described below is from this perspective.

1. The Requirements Team - Analyzes the capability gap and defines the operational requirements to be met by a successful candidate solution. These requirements are specified in terms of performance, cost, schedule and risk. There may also be a need to weight these criteria for future Request for Proposal (RFP) processes.

2. The Operational Architecture Team - Defines operational scenarios with which to evaluate the potential solution candidates. These involve military assessments of the threats that could be faced and the missions that need to be accomplished.

3. The System of Systems Architecture Team - Identifies components and systems that can contribute to meeting the capability requirements in the various operational scenarios. Data on the performance, cost, schedule and risk associated with these components is collected by this team to develop a set of solution candidates which will likely be a System of Systems (SoS).

4. The Investment Options Analysis Team - Conducts the trade studies attempting to determine an optimal mix of systems based on the data provided by the System of Systems Architecture Team, in the scenarios identified by the Operational Architecture Team to meet the requirements identified by the Requirements Team.

To help the Requirements Team, a number of frameworks have been designed. For performance requirements, there is a framework called PARRI which stands for: Persistence, Agility, Range, Reach and Information. There were some problems with the subjective manner in which these criteria were to be combined into an overall measure using a weighting and scoring approach. Therefore, we utilized an objective measure based on the performance required to meet the capability gap. For cost estimation, there is a framework called PRICIE which stands for: Personnel; Research and Development/Operational Research; Infrastructure and Organization; Concept, Doctrine and Collective Training; Information Technology; and Equipment, Supplies and Services. The Investment Options Analysis Team attempted to find the System of Systems that met the performance requirements at minimum cost. For schedule, the critical path method (CPM) was used to determine the minimum time that the solution could be implemented. This was nominally a target that we attempted to meet but we also calculated the performance obtained and costs incurred over time. For risk, there was a standard framework that required the estimation of the likelihood and consequences of various events. However, this concept was found to be too subjective for use in the Beta Trial. We developed a new model to estimate the likelihood that the option might be rejected because of unacceptably high political, economic, technological and/or social risks. All of the models used in the Beta Trial are documented in the Annexes to this report.

The Operational Architecture Team defined three areas for surveillance of the Northwest Passage: the Eastern Area, the Western Area, and the Main Channel. In each of these areas, they defined three operational scenarios: surface, subsurface and environmental. Therefore, there were nine operational scenarios for the surveillance mission. For the reconnaissance mission, the Operational Architecture Team defined four scenarios: Oil Spill, Willful Pollution, Search and Rescue, and Unidentified Object. For each of these four reconnaissance scenarios, the Operational Architecture Team defined the expected frequency and duration of these operations on an annual basis. These scenarios were linked to the performance requirements in the sense that the specified requirements were 100% coverage of the area for surveillance and 100% availability to respond to the reconnaissance operations.

The System of Systems Architecture Team identified systems that could be utilized to meet these requirements. There were nine systems identified by the System of Systems Architecture Team which included: Maritime Patrol Aircraft, Unmanned Aerial Vehicles, Land Based Radars, Ranger Patrols, Satellites, Frigates, Icebreakers, Submarines, and Remotely Deployed Sonars. Since this exercise was completed in the unclassified environment, only open source documents were used to estimate the performance attributes of these systems. We will not identify the systems by name, in this document, and the reader should consider the results in the Annexes as only a demonstration of the concepts of Capability Engineering and not dwell on the numerical accuracy of the estimates.

With this support from the other teams, it was a relatively straightforward process for the Investment Options Analysis Team to develop and apply a methodology that would help to determine the optimal SoS solution to meet the performance requirements at minimum cost. The documentation of this methodology and the use of the Phoenix-Integration software to implement this methodology will be the subject of the remainder of this paper. The next section will identify the approach used to model performance, cost, schedule and risk in the CapDEM Beta Trial. The subsequent section will discuss the integration of these models and the optimization using a genetic algorithm. The final section will provide some conclusions and recommendations for the Investment Options Analysis portion of the Capability Engineering process that were identified during the CapDEM Beta Trial. The Annexes provide more detailed descriptions of the submodels, the example data, and the results of the optimization.

2 Modelling for Option Analysis

The objective of the Investment Options Analysis process is to provide value-added to the Capability Engineering process by analyzing the requirements, scenarios and systems data to produce a recommendation to senior decision-makers on a short-list of solutions to the capability gap that is acceptable in terms of the four dimensions of performance, cost, schedule and risk. In the past, Investment Options Analysis has been restricted to a limited number of specific options which were analyzed manually according to simple criteria and then these criteria were scored and weighted to compare the options. This approach is deficient in a number of respects not least that the weights and scores are usually based on subjective judgment that can have a significant impact on the recommendation. We felt that it was extremely important that the Investment Options Analysis process be auditable and wherever possible be free of subjective opinions [4]. In other words, we wished to develop quantitative models using numerical estimates of the data and apply a rigourous process of analysis. These goals would not have been met by the original framework developed for the Capability Engineering process. Therefore, changes were made in the CapDEM Beta Trial that should be adopted for future refinement of the process. In the subsections below, we will discuss the four models for Performance, Cost, Schedule and Risk that were used in the Investment Options Analysis process.

2.1 Performance

The PARRI concept of Persistence, Agility, Range, Reach and Information identifies the dimensions of performance that should be examined in Intelligence, Surveillance and Reconnaissance Support Operations [5]. The Requirements Team developed specific criteria according to the PARRI framework for the CapDEM Beta Trial. These needed to be defined according to the operational scenarios developed by the Operational Architecture Team. Therefore, we had performance requirements for each of the five PARRI dimensions (with many quantitative subcriteria) for each of the nine surveillance and four reconnaissance operational scenarios. This led to a huge number of performance requirements which in principle should not be a problem for a large team of analysts with access to large quantities of data and a sophisticated suite of computer models. Since this was only a trial, we had only a small team, a dearth of performance models at our disposable and limited access to data. Therefore, the Investment Options Analysis Team was directed by the SoS Architecture Team Leader to simplify the problem greatly in the analysis stage and consider only coverage for the surveillance scenarios and availability for the reconnaissance scenarios.

There are two competing issues that need to be considered in this approach to performance modelling. The first is the comparison of the options according to performance. The original CapDEM framework suggested a process in which performance requirements could be variable. It used subjective weights and scores to rank the options in terms of performance. The Investment Options Analysis team felt that this approach was too subjective to be used in our models. It was not clear how the weights would be determined and, if different weights were used, how that would impact on the recommendation. Therefore, we took the approach that the performance requirements would be specified in terms of minimum acceptable criteria. If the solution failed in one of the criteria, it would be rejected from future consideration.

This led to the second issue that relates to the performance requirements: namely, the importance of specifying truly essential requirements and not ‘gold plating’. The latter course of action will obviously increase the cost substantially and may put the approval of the project at risk. It may even lead to the situation in which there are no feasible solutions that meet the requirements. For example, the Office of Auditor General noted that the department specified essential requirements in the procurement of the Griffon helicopter and the Maritime Coastal Defence Vessel, only to find that the systems under consideration could not meet these requirements. Then the department went back and redefined the essential requirements [6].

Concerning the weighting of the criteria, we note that even though we do not recommend this process because of its subjective nature, it is often used in practice. In fact, Public Works and Government Services Canada has developed guidelines for evaluating Requests for Proposal and although they recommend, as we do, the approach of finding a minimum cost solution that meets the essential requirements or finding a maximum performance solution that is within a specified budget, they also describe methods that involve weighting and scoring solutions subjectively [7].

Annex A provides more details on the performance model that was used in the CapDEM Beta Trial.

2.2 Cost

The first thing that must be noted about cost in the department is that we are talking about opportunity cost. That is, in the CapDEM Beta Trial, we are describing the choice of expending a certain amount of resources from the relatively fixed defence budget on the Northwest Passage missions rather than applying these resources on some other mission the department may desire. The Director General of Strategic Planning (DGSP) has recently developed a 30-Year model of capability costs [8]. Using this model, we were able to estimate the annual average expenditures for the existing equipment in our defence inventory. It was more problematic to estimate the cost of systems that were not in our current inventory; however, the PRICIE framework was useful as a checklist to examine the full range of possible expenditures.

There were a number of issues that were resolved by using the DGSP 30-Year Model.

1. The model considers a sufficiently long time frame to allow for the possible replacement of the systems in the database. Thus, using this data is equivalent to estimating the cost of maintaining the capability indefinitely. Therefore, there is no need to consider phasing out and phasing in different generations of equipment.

2. The model uses current year dollars; therefore, there is no need to consider the problems associated with inflation or discounting.

3. The model estimates the annual average cost of ownership of the capability which includes acquisition costs, capital upgrades and modifications, national procurement, military and civilian personnel costs, infrastructure costs, research and development costs, individual and collective training costs, etc. Therefore, the breakout of the costs into the PRICIE components for inspection by subject matter experts is greatly facilitated.

4. The model computes the unit cost of a capability component. In our model, the number of individual systems is used as a variable in the mix to produce a SoS option while the unit cost is an input parameter.

One thing that should be noted is that our model used only the annual average unit costs and did not actually break down the costs into the PRICIE components. The breakdown of the costs into the PRICIE components was done in the CapDEM framework primarily for presentation to decision-makers.

Annex B provides the details of the cost model.

2.3 Schedule

A critical path approach can be used to estimate the time required to implement the SoS option. This implies that the system that takes the longest to implement is the limiting factor in the schedule. We assumed that all of the systems can be implemented independently which may not be the case in reality.

In this effort, the PRICIE framework was also useful because it highlighted all of the elements related to the support of the capability. Each of the elements of the PRICIE framework was broken out according to a series of implementation projects necessary to introduce or reallocate the system components. In principle, this would be a highly complex process requiring sophisticated project management software that can handle multiple simultaneous projects.

In the CapDEM Beta Trial, we used a much simpler model that involved only fixed and variable elements in the schedule. That is, it was assumed that the initiation of a project required a certain period of startup and that each additional system that was introduced required a certain additional unit of time to bring on board. There was also a concept in the schedule model that assumed that systems that had already been approved for use in this mission could be quickly reallocated whereas systems that were recommended in an option over and above the approved number would require a project to be setup and therefore take more time to reallocate or acquire.

The schedule was not considered a limiting factor in the model the way cost and performance were. It was simply calculated for the SoS option and displayed graphically in terms of the performance that was obtained and the costs that were incurred during each progressive stage of the implementation.

Annex C provides the details of the schedule model.

2.4 Risk

The original approach for analyzing Risk suggested in the CapDEM framework was based on an estimation of the likelihood and consequences of various events occurring and the summing of the product of these subjective estimates into a risk score for the option. The Investment Options Analysis Team had difficulty conceiving of a method by which this approach could be made objective and auditable. Therefore, on our own initiative, we designed a completely new approach.

We wished to quantify the political, economic, technological and/or social risks. We felt that a proxy measure of this risk could be the risk of the decision-maker rejecting the SoS option because it required too many resources. The first assumption that we made was that the decision-maker had already approved certain resources for the mission[1]. Some of these approved resources might be new to the Canadian Forces, such as Icebreakers, and others might need to be taken away from other missions, such as MPAs. From the point of view of the risk of the decision-maker rejecting the option, using these approved resources can be considered a negligible risk.

To meet the performance requirements, an SoS option may require more (and different) resources than had been originally approved. Our model of risk attempts to provide a quantitative estimate of the probability of rejecting the SoS because it requires more resources than are acceptable to the decision-maker. We assumed that this could be estimated based on the amount of resources that need to be reallocated to the mission to meet the performance requirements over and above those that have already been approved.

In Annex D, we provide a detailed description of the quantitative model. However, to give a flavour of the risk calculations, we will consider two examples: first, a medium cost resource, the MPA, and second, a low cost resource, the UAV. Let us say that two MPA have been approved for the mission already and the SoS option requires only two MPA. Then their contribution to the risk of the decision-maker rejecting the option would be 'negligible'. If three MPA are recommended in the SoS option, there might be a 'medium' risk associated with this reallocation or acquisition of one additional MPA because the MPA is a medium cost resource. If four MPA are recommended, the risk might be 'high' because two MPA would need to reallocated or acquired. Thus the risk is a monotonically increasing function of the number of systems recommended over and above those that have been approved.

Now compare this to the situation in which one additional UAV is recommended in the SoS option over those that have been approved. The risk of rejecting the option because of the requirement to reallocate the extra UAV would be low since the UAV is a low cost resource. Therefore, the higher the cost of the resource, the greater the risk of rejecting the option if it has not already been allocated to the mission and needs to be acquired or reallocated from another mission.

The goal of the Investment Options Analysis Team was to find an SoS option that meets the performance requirements at minimum cost. We used the computerized search algorithm that will be described in more detail in the next section to find this option. The Investment Options Analysis Team developed a quantitative model of risk based on the proxy measure of the probability of the decision-maker rejecting an individual SoS option based on the amount of resources that are required over and above the approved allocation. This quantitative model was required if risk were to be considered in the optimization process. We could have used our search algorithm to find the SoS option that meets the performance requirements at minimum cost

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[1] It was not known without detailed analysis if these approved resources would be capable to meeting the performance requirements.

and minimum risk. However, since the model of risk we developed appeared to be more speculative than the performance requirements and the cost models, it was decided that it would not be included in the optimization at this time. Therefore, the quantitative risk results were calculated for the SoS option but simply provided as information to the decision-maker in a qualitative manner in terms of a 'high', 'medium', 'low' and 'very low' scale.

The exact details of our approach to risk are provided in Annex D.

3 Optimization for Option Analysis

The SoS Architecture Team provided the data on performance and schedule to support these submodels. The Investment Options Analysis used the data from the DGSP 30-Year Model in the cost and risk submodels. For the CapDEM Beta Trial, these submodels were relatively simple spreadsheets. In the future, one would expect that these models might be too complex to be handled by spreadsheets, especially the performance submodel. The goal of the optimization process was to find the SoS option that met the performance criteria at minimum cost. Even with these simple models, the integration and optimization process had to be supported by a sophisticated software system developed by Phoenix-Integration Inc. [9]. In the sections below, the integration process will be discussed first and the optimization process will be discussed next. The details of the optimization process are provided in Annex E.

3.1 Integration of the Submodels

In the Elaboration phase of the CapDEM Beta Trial, the Investment Options Analysis Team was provided with a suite of tools from Phoenix-Integration Inc. with which to conduct trade studies. The first tool that we will discuss is called Model Center and is used to integrate a number of submodels of different types into a larger combined model.

In the case of the CapDEM Beta Trial, we had four separate submodels (for performance, cost, schedule and risk) which would be used to evaluate a SoS option from different perspectives. Each of these submodels had its own internal logic and data parameters. However, they were setup to consider an SoS option in a common format. Therefore, they could be linked together according to the SoS option characteristics.

For example, an SoS option might consist of 5 MPA, 6 UAV, 3 Frigates, and 3 Icebreakers employed in some particular configuration in the 13 scenarios. This SoS option with its allocation to the scenarios would have certain performance, cost, schedule and risk characteristics that would be calculated by the submodels.

One submodel does not need to know the internal workings of the other submodels. It only needs to know the nature of the input or output connection. Therefore, the model is taken as an entity and a tool, called a 'wrapper', is built around the model to show the other models only its input and output connections. Using this wrapper, the Phoenix-Integration software can connect submodels via their input and output and thereby carry out optimization processes or conduct sensitivity analysis. For the spreadsheets that were used in the CapDEM Beta Trial, the Excel Wrapper Plug-In in Model Center was used which made the integration fairly simple. For more complex models, one might need to build more involved wrappers for which Phoenix-Integration provides another product called Analysis Server. We did not investigate the use of Analysis Server during the Beta Trial but its use would be highly likely in the future.

3.2 Use of a Genetic Algorithm

With the Model Center, there are a number of analysis and optimization tools. For the CapDEM Beta Trial and likely for future SoS optimization, the tool that is most useful is called Darwin and uses a genetic algorithm to optimize an objective function subject to constraints over a series of design parameters. We found this tool to be flexible and robust for the SoS optimization compared to other optimization techniques that were available, such as the gradient method, because our design space was primarily integer values and the objective and constraint functions were highly non-linear and discontinuous.

As the name would suggest Darwin uses an evolutionary process to find the optimal solution to the problem that is specified. In the CapDEM Beta Trial, we can think of a genetic code of 13 genes, one for each scenario, in which each gene is a string of nine integers, one for each system type, where each integer represents the number of systems on type j used in scenario i. The genetic algorithm begins by generating a random population each with its own genetic material. A certain number of these individuals survive based on fitness (i.e. performing well in the objective and meeting the constraints) and reproduce based on genetic mutation and genetic mixing to produce a new population. Over a number of generations, the population adapts to the problem environment and the algorithm can identify the 'most fit' individual found so far in terms of the objective and the constraint.

In Figure 1, we see the results of a cost minimization subject to a performance constraint of 100% coverage and 100% availability. We can see that the genetic algorithm started at a random solution and over 100 generations improved on this solution until it settled down at about $900M per year.

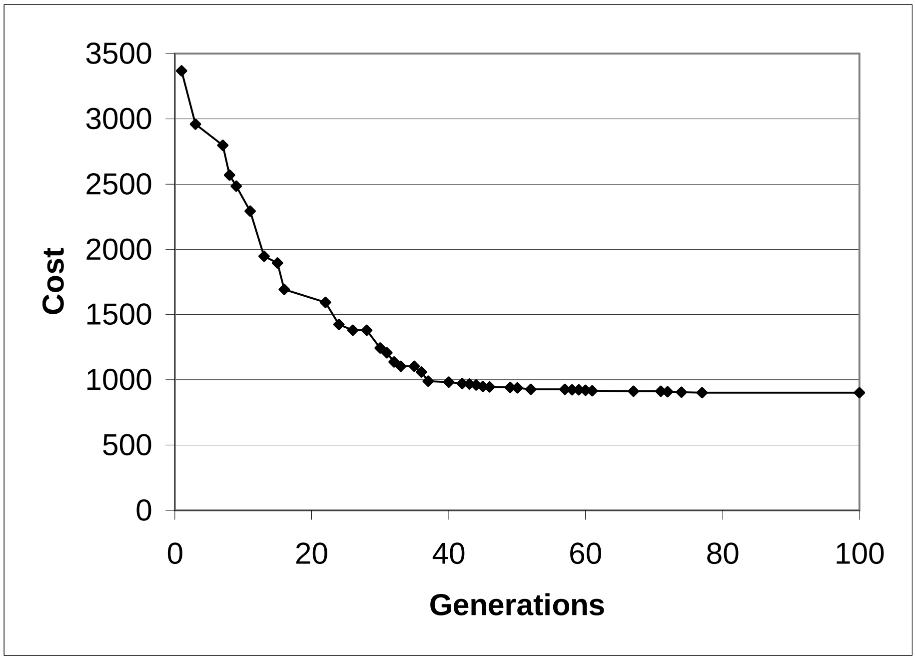

Figure 1: *Results of a Cost Minimization*

In Figure 2, we see the results of a performance maximization subject to a budget constraint of $1,000M per year. We can see that it took a number of generations to produce a feasible solution and then the performance began to increase, rapidly at first, until it settled down at about 110%. The extra 10% represents redundancy in the performance criteria.

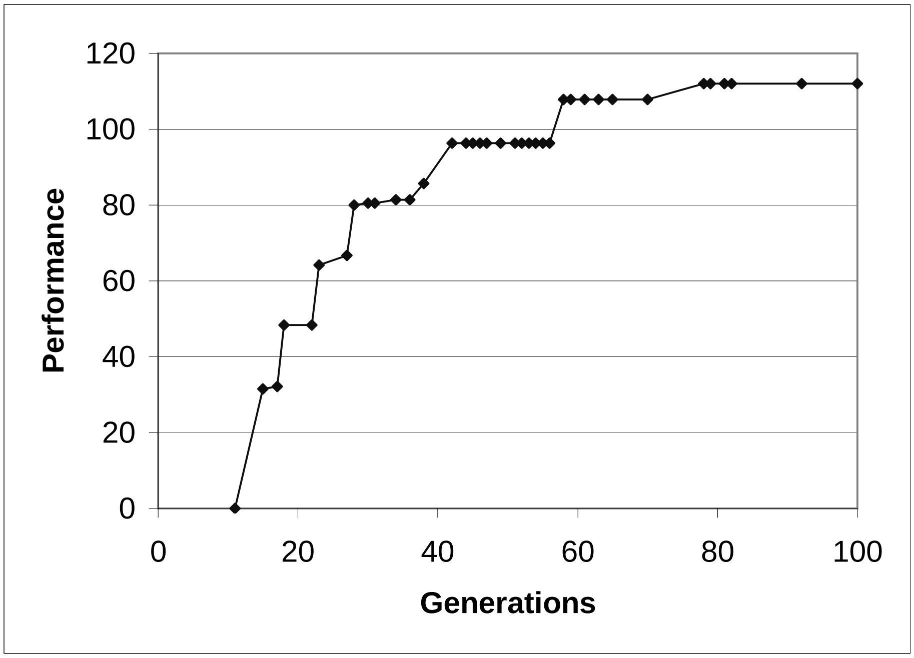

Figure 2: *Results of a Performance Maximization*

4 Conclusions and Recommendations

In this section, we will combine conclusions, recommendations and future work with regard to the performance, cost, schedule and risk submodels, and the Phoenix-Integration software.

In the Performance submodel, the PARRI framework was proposed in the original process. Although, this framework is a good checklist for the performance requirements, we noted that it is important to ensure that only the truly essential performance requirements are considered as constraints to the optimization process. We do not support the use of subjective estimation of these performance requirements. Instead we would like to see an objective measure of the performance that can be used as a constraint or can be maximized. In the future, we expect that the performance model will be much more complicated than that used in the CapDEM Beta Trial; however, the same basic concepts of meeting a list of essential requirements should be applied.

In terms of the Cost submodel, we found the DGSP 30-Year database quite useful to estimate annual average costs for existing systems and that the PRICIE framework was useful for future systems. These cost estimates for each system were used in the optimization process to find the minimum cost mix of systems that met the performance requirements. One could turn this around, as we have shown, to find the mix of systems that provided the maximum performance within a fixed budget. Either of these approaches are recommended methods of developing a SoS option.

The Schedule submodel is based on the reallocation of systems over and above those that have already been approved. We assumed a simple model of setup time and incremental time and assumed that each system implementation project would be independent. This would probably not be acceptable in a real decision analysis. There would likely be a requirement to use sophisticated project management software that can handle multiple simultaneous projects. However, the PRICIE framework remains an excellent tool for considering all of the support elements in the planning of a new capability. We do not recommend that schedule be used as an objective or a constraint in the optimization even though this is possible with the genetic algorithm software. Instead, we found it useful to present the capability and cost graphically as a function of implementation time for decision support.

The Risk submodel was the largest departure from the CapDEM process framework that we made during the project. We developed a quantitative model based on the risk of rejecting an option as a function of the amount of resources that would need to be diverted from other activities in the department. We also developed a qualitative categorization of the risk for presentation to decision-makers. One of the benefits of this approach was that the qualitative model was explanable and auditable. However, it would need further validation to ensure it meets the needs of future decision processes. Risk was a concern and could have been minimized or used as a constraint; however, we felt that this model was too immature for this type of use at this time.

The Phoenix-Integration Model Center tools look extremely promising for future use in decision support. The ability to integrate models of different types is a novel capability that the author has not seen in other software tools. In the CapDEM Beta Trial, we restricted the submodel formulation to spreadsheets; however, the Phoenix-Integration software has the capability to develop ‘wrappers’ for all kinds of models and this will be needed as the submodels become more complex.

The other aspect of the Phoenix-Integration toolset that we found extremely useful was the Darwin genetic algorithm. This optimization tool was found to be flexible and robust considering the non-linear and discontinuous functional expressions that we were using in our submodels. It was highly effective at helping us determine the optimal SoS option to meet the performance constraints at minimum cost. It should be used in future SoS optimization studies.

The conclusions of the Investment Options Analysis Team based on the CapDEM Beta Trial experience are:

1. The concept of considering the four dimensions of performance, cost, schedule and risk is an excellent way to compare various SoS options. In particular, we believe that the measurement of these dimensions should be based on objective and auditable data. We rejected methods in the CapDEM framework that involved subjective weighting and scoring of the options. Unfortunately, modeling and data resources limited our ability to realistically demonstrate the full potential of this alternative approach. Therefore, we look forward to the Gamma Trial to refine these techniques with the use of a new framework.

2. Although, we only attempted to find the SoS option that met the performance requirements at minimum cost, the ultimate goal might be to determine the SoS option that meets the performance and schedule requirements at minimum cost and minimum risk. This approach would be possible using the Phoenix-Integration software by integrating submodels for all four dimensions and applying the Darwin genetic algorithm to find the optimal SoS option.

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Annex A: Performance Submodel

There are 13 scenarios in the performance model: nine surveillance and four reconnaissance. There are nine systems being considered to fulfill the requirements. Each system can contribute to the requirement. The performance of the SoS option in a scenario is the sum of the performance of each of the systems.

The results for the nine surveillance scenarios are shown in Tables A.1 to A.9. For the surveillance scenarios, we were given two measures of performance from the SoS Architecture Team: percentage coverage and percentage availability. The product of these two values in percentage terms is shown in the multiplier column. Then the number of systems[2] identified for this scenario is multiplied by this multiplier column to obtain the system performance. The sum of the system performance is used to estimate the scenario performance.

It should be noted that in the surveillance scenarios, we assumed that if a system was used in one scenario, it was available for the other two scenarios in the same area. This meant that if the system was required for subsurface surveillance, it was also available for surface and environmental surveillance even though more specialized systems might be more capable in these other scenarios.

For the reconnaissance scenarios, the two measures that were used to calculate the multiplier were: the percentage of the requirement and the availability as a percentage (see Tables A.10 to A.13). In this case, the availability was divided by the requirement to obtain the multiplier column in percentage terms which was multiplied by the number of systems to obtain the system performance. Again the sum of the system performance was used to estimate the scenario performance.

In the Beta Trial, the performance data was provided by the SoS Architecture Team to demonstrate the concept and cannot be considered realistic.

Finally, the overall performance was estimated by taking the minimum over all of the scenarios. That is, we assumed that 100% overall performance implied at least 100% performance in all of the 13 scenarios. Values greater than 100% were assumed to imply a level of redundancy. The 100% overall performance requirement (i.e. 100% performance in all 13 scenarios) was used as a constraint in our optimization and the results are shown in Table A.14.

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[2] The number of systems is calculated by the genetic algorithm.

Table A.1: *Performance in Surveillance West Surface*

Systems	Units	Percentage Coverage	Percentage Availability	Multiplier	System Performance	Scenario Performance
System 1	2	166	17	28	56	
System 2	0	230	67	154	0	
System 3	0	20	96	19	0	
System 4	0	0.3	17	0	0	
System 5	0	100	7	7	0	
System 6	0	32	83	27	0	
System 7	1	64	83	53	53	
System 8	0	100	100	100	0	
System 9	0	38	83	32	0	110

Table A.2: *Performance in Surveillance West Subsurface*

Systems	Units	Percentage Coverage	Percentage Availability	Multiplier	System Performance	Scenario Performance
System 1	2	166	17	28	56	
System 2	0	0	0	0	0	
System 3	0	0	0	0	0	
System 4	0	0	0	0	0	
System 5	0	0	0	0	0	
System 6	0	32	83	27	0	
System 7	1	64	83	53	53	
System 8	0	0	0	0	0	
System 9	0	38	83	32	0	110

Table A.3: *Performance in Surveillance West Environmental*

Systems	Units	Percentage Coverage	Percentage Availability	Multiplier	System Performance	Scenario Performance
System 1	2	166	17	28	56	
System 2	0	230	67	154	0	
System 3	0	0	0	0	0	
System 4	0	0.3	17	0	0	
System 5	0	100	7	7	0	
System 6	0	32	83	27	0	
System 7	1	64	83	53	53	
System 8	0	0	0	0	0	
System 9	0	38	83	32	0	110

Table A.4: *Performance in Surveillance East Surface*

Systems	Units	Percentage Coverage	Percentage Availability	Multiplier	System Performance	Scenario Performance
System 1	1	260	17	44	44	
System 2	0	360	67	241	0	
System 3	0	32	96	31	0	
System 4	0	0.47	17	0	0	
System 5	0	100	7	7	0	
System 6	0	50	83	42	0	
System 7	1	100	83	83	83	
System 8	0	100	100	100	0	
System 9	0	38	83	32	0	127

Table A.5: *Performance in Surveillance East Subsurface*

Systems	Units	Percentage Coverage	Percentage Availability	Multiplier	System Performance	Scenario Performance
System 1	1	260	17	44	44	
System 2	0	0	0	0	0	
System 3	0	0	0	0	0	
System 4	0	0	0	0	0	
System 5	0	0	0	0	0	
System 6	0	50	83	42	0	
System 7	1	100	83	83	83	
System 8	0	0	0	0	0	
System 9	0	38	83	32	0	127

Table A.6: *Performance in Surveillance East Environmental*

Systems	Units	Percentage Coverage	Percentage Availability	Multiplier	System Performance	Scenario Performance
System 1	1	260	17	44	44	
System 2	0	360	67	241	0	
System 3	0	0	0	0	0	
System 4	0	0.47	17	0	0	
System 5	0	100	7	7	0	
System 6	0	50	83	42	0	
System 7	1	100	83	83	83	
System 8	0	0	0	0	0	
System 9	0	38	83	32	0	127

Table A.7: *Performance in Surveillance Main Channel Surface*

Systems	Units	Percentage Coverage	Percentage Availability	Multiplier	System Performance	Scenario Performance
System 1	2	96	17	16	33	
System 2	0	133	67	89	0	
System 3	0	12	96	12	0	
System 4	0	4	17	1	0	
System 5	0	100	7	7	0	
System 6	3	19	83	16	47	
System 7	1	37	83	31	31	
System 8	0	100	100	100	0	
System 9	0	38	83	32	0	111

Table A.8: *Performance in Surveillance Main Channel Subsurface*

Systems	Units	Percentage Coverage	Percentage Availability	Multiplier	System Performance	Scenario Performance
System 1	2	96	17	16	33	
System 2	0	0	0	0	0	
System 3	0	0	0	0	0	
System 4	0	0	0	0	0	
System 5	0	0	0	0	0	
System 6	3	19	83	16	47	
System 7	1	37	83	31	31	
System 8	0	0	0	0	0	
System 9	0	38	83	32	0	111

Table A.9: *Performance in Surveillance Main Channel Environmental*

Systems	Units	Percentage Coverage	Percentage Availability	Multiplier	System Performance	Scenario Performance
System 1	2	96	17	16	33	
System 2	0	133	67	89	0	
System 3	0	0	0	0	0	
System 4	0	4	17	1	0	
System 5	0	100	7	7	0	
System 6	3	19	83	16	47	
System 7	1	37	83	31	31	
System 8	0	0	0	0	0	
System 9	0	38	83	32	0	111

Table A.10: *Performance in Reconnaissance Oil Spill*

Systems	Units	Percentage Coverage	Percentage Availability	Multiplier	System Performance	Scenario Performance
System 1	0	360	180	50	0	
System 2	2	360	240	67	133	
System 3	0	360	0	0	0	
System 4	0	360	220	61	0	
System 5	0	360	30	8	0	
System 6	0	360	340	94	0	
System 7	0	360	320	89	0	
System 8	0	360	0	0	0	
System 9	0	360	340	94	0	133

Table A.11: *Performance in Reconnaissance Willful Polluter*

Systems	Units	Percentage Coverage	Percentage Availability	Multiplier	System Performance	Scenario Performance
System 1	0	192	96	50	0	
System 2	2	192	128	67	133	
System 3	0	192	0	0	0	
System 4	0	192	0	0	0	
System 5	0	192	16	8	0	
System 6	0	192	480	250	0	
System 7	0	192	320	167	0	
System 8	0	192	0	0	0	
System 9	0	192	480	250	0	133

Table A.12: *Performance in Reconnaissance Search and Rescue*

Systems	Units	Percentage Coverage	Percentage Availability	Multiplier	System Performance	Scenario Performance
System 1	0	720	360	50	0	
System 2	2	720	480	67	133	
System 3	0	720	0	0	0	
System 4	0	720	0	0	0	
System 5	0	720	60	8	0	
System 6	0	720	1400	194	0	
System 7	0	720	1000	139	0	
System 8	0	720	0	0	0	
System 9	0	720	1400	194	0	133

Table A.13: *Performance in Reconnaissance Unidentified Object*

Systems	Units	Percentage Coverage	Percentage Availability	Multiplier	System Performance	Scenario Performance
System 1	0	1200	600	50	0	
System 2	2	1200	800	67	133	
System 3	0	1200	0	0	0	
System 4	0	1200	0	0	0	
System 5	0	1200	100	8	0	
System 6	0	1200	9000	750	0	
System 7	0	1200	5000	417	0	
System 8	0	1200	0	0	0	
System 9	0	1200	9000	750	0	133

Table A.14: *Calculation of Overall Performance*

Scenario Type	Area	Scenario Name	Perf
SURV	West	Surface	110
SURV	West	Subsurface	110
SURV	West	Environ	110
SURV	East	Surface	127
SURV	East	Subsurface	127
SURV	East	Environ	127
SURV	Main	Surface	111
SURV	Main	Subsurface	111
SURV	Main	Environ	111
RECCE		Oil Spill	133
RECCE		Willful Polluter	133
RECCE		SAR	133
RECCE		Unidentified Object	133
		Minimum	110

Annex B: Cost Submodel

To compute the cost of the SoS option, we need to know the number of units of each system type that will be employed and the average annual cost of each of these system types. The average annual cost of the systems that are currently in our inventory was found in the DGSP 30-Year Model. For entirely new systems, reasonable proxy systems could be found in the DGSP Model. The number of systems of each type was found by the genetic algorithm which was attempting to meet the performance constraint at minimum cost.

In the performance submodel, we had two types of scenarios: surveillance and reconnaissance. There were nine surveillance scenarios; three in each of the regions (East, West and Main Channel). We assumed that if a system was used in one of these scenarios in a particular region, it was also available for the other scenarios in the region. Therefore, we needed only to consider the systems assigned to each of the regions in the surveillance scenarios and not the scenarios themselves. For the reconnaissance scenarios, they were considered to be independent of each other and; therefore we needed to sum the systems assigned to each of these scenarios.

We defined 'named ranges' in the spreadsheets to be used in the Model Center linking process to represent the systems required for Surveillance Eastern Area (SEA), Surveillance Western Area (SWA), Surveillance Main Channel (SMC), Reconnaissance Oil Spill (OS), Reconnaissance Search and Rescue (SAR), Reconnaissance Unidentified Object (UO) and Reconnaissance Willful Polluter (WP) in each option. The Cost Model takes as input the values in these named ranges and computes the number of systems of each type for the SoS option and uses them in the cost calculation.

The results in Table B.1 show the cost of the optimal SoS option when cost was minimized subject to the 100% overall performance constraint. For simplicity, we considered the number of systems in whole units. That is, we did not consider flying hours or sea days but instead considered aircraft or ships required.

Table B.1: *Calculation of Average Annual Cost in $M*

System	Units	Annual Cost per Unit	System Cost
System 1	5	42.1	210.5
System 2	8	4.4	35.2
System 3	0	2.6	0
System 4	0	3.7	0
System 5	0	64.0	0
System 6	3	89.3	267.9
System 7	3	124.8	374.4
System 8	0	2.9	0
System 9	0	131.0	0
Total			888.0

Annex C: Schedule Submodel

In the Schedule Model, like the Cost Model, we compute the total number of systems of each type from the performance model's named ranges: SEA, SWA, SMC, OS, SAR, UO, and WP.

An internal parameter to the model is the number of systems that are already available for this mission. We assume that this number of systems can be deployed relatively quickly.

Therefore, we need only consider the number of systems over and above those that are available. If there are a number of such systems, then it is necessary to setup a project office with an associated fixed setup time in years. For each individual system that needs to be deployed, there is also an incremental time to deploy the system over and above the fixed time. We use these two parameters to calculate the time in years to deploy the systems over and above the systems that are available.

We assume that each of the systems are deployed independently. Therefore, the maximum system time is taken as the time to implement each option. Schedule was not used as an objective or a constraint. It was simply calculated for each option. The results for the optimal SoS option are shown in Table C.1.

Table C.1: *Calculation of Time to Implement in Years*

System	Units	Approved	Setup	Incremental	System Time
System 1	5	3	5	0.5	6
System 2	8	0	3	0.5	7
System 3	0	0	5	0.25	0
System 4	0	4	0	0	0
System 5	0	1	7	7	0
System 6	3	0	5	1	8
System 7	3	2	5	1	6
System 8	0	2	5	1	0
System 9	0	1	5	1	0
Maximum					8

Annex D: Risk Submodel

The Risk Model was developed by the Investment Options Analysis Team as a simple method of objectively quantifying the political, economic, technological and/or social risks of an SoS option. The basic concept behind the model is that political, economic, technological and/or social risks associated with an SoS option can be approximated by the probability that the option will be rejected out of hand by the decision-maker because it requires too many resources. Thus, the risk is a function of the risks associated with each of the systems involved. We assume that if a certain number of these systems have already been approved for this operation, the decision-makers have determined that the risk associated with this allocation is negligible. Then we need only to consider the risk associated with recommending in our SoS option more systems than have already been approved.

The Poisson probability distribution was chosen to estimate this risk. The interpretation here is that if we recommend two systems, for example, to be allocated to the mission over and above those that have been already approved, then we can use the Poisson Probability distribution to estimate the confidence that this recommendation will be approved based on the system not being rejected with 0, 1 or 2. The confidence is estimated as one minus the cumulative Poisson probability.

The Poisson distribution requires only one parameter and we will model the value of this parameter as a function of system cost with the relative baseline value of 2.0 for the highest cost system. The parameter is calculated as (Cost of System + Cost of Highest Cost System)/(Cost of System).

For example, for System 1, the cost in Table B.1 is 42.1 and the cost of System 9 is 131.0. Therefore, the Poisson parameter is $(42.1 + 131.0)/42.1 = 4.1$, and the risk of rejecting the option because of the reallocation of two units of System 1, over and above the three already approved, is estimated as the probability according to a Poisson distribution of having 2 or less events when the mean is 4.1; namely 22%. The confidence of approval of the reallocation is one minus the risk of rejecting the option. That is, $(1 - 22\%) = 78\%$.

Then the overall SoS option risk is assumed to be a function of the system risks. That is, the option will be rejected if any of the system reallocations are rejected. This is assumed to be similar to a serial connection in reliability theory. In Table D.1, we have a system confidence of 78% for the reallocation of two units of System 1, 100% for reallocation of six units of the relatively inexpensive System 2 (based on the Poisson calculation), 100% for the System 6 (based on the fact that three systems have already been allocated), and 61% for the reallocation of one unit of System 7. Therefore, the Option Risk is estimated to be the serial connection of these four system risks, that is $(1 - (0.78)(1)(1)(0.61)) = (1 - 0.47) = 0.53$.

Table D.1: *Calculation of Risk*

System	Units	Approved	Parameter	Confidence
System 1	5	3	4.112	0.78
System 2	8	0	30.773	1.00
System 3	0	3	51.385	1
System 4	0	4	36.405	1
System 5	0	1	3.047	1
System 6	3	3	2.467	1
System 7	3	2	2.050	0.61
System 8	0	1	51.385	1
System 9	0	1	2.000	1
Overall Risk				0.53

Although this is calculated quantitatively, it can be presented to the decision-maker qualitatively using the following categorization: the risk of rejecting the option is categorized as Very Low, if the probability estimate is less than 1%. It is Low, if the probability estimate is between 1 and 10%. It is Medium, if the probability is between 10 and 25%. It is High, if the probability is between 25 and 50%, and it is Very High, if it is above 50%. Therefore on our qualitative risk scale, the SoS Option in Table D.1 ranks as Very High.

There are a number of ways that one might consider to reduce the risk based on this model; the simplest being to gain approval for more of the recommended systems to be assigned to this mission. Another possibility is to reduce the performance requirement marginally and see if the number of high risk systems can be reduced. Finally, one might look at increasing the budget thereby modify the mix of systems. This might utilize more of the systems that have already been approved for the mission and require less reallocation.

There were suggestions during the CapDEM Beta Trial that risk should be minimized in the objective function. This is possible in the Darwin genetic algorithm. However, even though the model that we developed for risk was quantitative, it was somewhat esoteric and arbitrary, and therefore we felt that using it as an objective or a constraint was premature at this time. More work is required to validate this approach.

Annex E: Obtaining the Optimization Results

The Phoenix-Integration Model Center was used to conduct the optimization process to find the SoS option that provided 100% coverage and 100% availability in the scenarios at minimum cost.

We began with four Excel spreadsheets; one for each of the submodels of cost, performance, risk and schedule, as described in Annexes A through D. In each of these spreadsheets, we defined 'named ranges' to be used in the Model Center linking process. There were named ranges for the systems to be used in Surveillance Eastern Area (SEA), Surveillance Western Area (SWA), Surveillance Main Channel (SMC), Reconnaissance Oil Spill (OS), Reconnaissance Search and Rescue (SAR), Reconnaissance Unidentified Object (UO) and Reconnaissance Willful Polluter (WP). These were considered input values in the Model Center software since they contained constant values. There were also named ranges for the output: Total Cost in the Cost spreadsheet, Overall Performance in the Performance spreadsheet, Maximum Time in the Schedule spreadsheet and Total Risk in the Risk spreadsheet. These were considered to be output in the Model Center software since these cells contained formulae.

The first step was to integrate the four spreadsheets in the Model Center software. This was done by dragging and dropping the Excel icon from the plug-in portion of the Model Center page into the model section and identifying the Excel spreadsheets by path name. We automatically imported all of the named ranges in the spreadsheets into the Model Center integrated model. For the Cost spreadsheet, we also set the named ranges OS, SAR, SEA, SMC, SWA, UO, and WP to 'int[]' with a lower bound of 0 and an upper bound of 3. This was used to make the design variables integers between 0 and 3 for all of the scenarios.

The second step was to link the spreadsheets. We held the cursor over the cost spreadsheet icon until a 'link' cursor was shown and then dragged the cursor over to the risk spreadsheet icon. Then we linked all the named ranges using the automated features since they had identical names in both spreadsheets. We linked the risk spreadsheet to the schedule spreadsheet and the schedule spreadsheet to the performance spreadsheet.

The third step was to drag a Darwin icon onto the model page and this opened up the Darwin page. From the model tree on the left hand side of the Model Center page, we opened the individual models and dragged the 'Total Cost' into the objective panel. The default is to minimize, so we did not need to change it. We then dragged the 'Overall Performance' into the constraints panel and set the lower bound to 100. Then we individually dragged the input variables which were labelled OS, SAR, SEA, SMC, SWA, UO, and WP from the Cost spreadsheet to the design variables panel of the Darwin window.

The fourth step was to set the Darwin optimization options. We clicked on the Options button to get the Options page and turned off the defaults setting. We reset the Population Size to 200, the Random Number seed to 10 (when you use different seeds you get slightly different results), and Stopping Mode as Fixed Generations, and the Number of Generations to 100. Then we clicked 'Okay' on the Options Page and 'Okay' on the Darwin page and saved the model.

We clicked the Darwin icon again and ran the genetic algorithm which took about 90 minutes to run on our Dell Pentium 'M' laptop computer. When the algorithm was finished, we inspected the the spreadsheets to find the results shown in Annexes A through D.

List of Abbreviations

CapDEM	Collaborative Capability Definition, Engineering and Management
CORA	Centre for Operational Research and Analysis
CPM	Critical Path Method
DGSP	Director General Strategic Planning
DRDC	Defence Research and Development Canada
MPA	Maritime Patrol Aircraft
NDHQ	National Defence Headquarters
OS	Oil Spill
PARRI	Persistence, Agility, Range, Reach and Information
PRICIE	Personnel; Research and Development/Operational Research; Infrastructure and Organization; Concept, Doctrine and Collective Training; Information Technology; and Equipment, Supplies and Services
SAR	Search and Rescue
SEA	Surveillance Eastern Area
SMC	Surveillance Main Channel
SoS	System of Systems
SWA	Surveillance Western Area
UAV	Unmanned Aerial Vehicle
UO	Unidentified Object
WP	Willful Polluter

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The CapDEM Beta Trial was intended to test the Capability Engineering process using a study of the Surveillance and Reconnaissance of the Northwest Passage. The project began with series of briefings in NDHQ and DRDC Ottawa on 1-3 November 2005 and completed on 1 March 2006. The author was a member of the Investment Options Analysis Team and the following paper documents the use of the Phoenix-Integration Model Center in the optimization of the System of Systems options based on performance, cost, schedule and risk. A genetic algorithm called Darwin, available with the Model Center software, was found to be flexible and robust for this complex problem that involves a huge integer-based solution space and highly non-linear, discontinuous functional expressions for the objective and constraints. The author is confident that the Phoenix-Integration software will prove valuable in future real-life decision analyses.

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