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Evaluation of Net-centric Command and Control via a Multi-resolution Modeling Evaluation Framework

Modeling and Simulation

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Abstract

Net-centric transformation and its associated practice of portfolio management require Department of Defense (DOD) managers to understand the effects various net-centric command and control (C2) services have on operational outcomes. This paper discusses an approach developed by the Johns Hopkins University Applied Physics Laboratory (JHU/APL) to qualitatively and quantitatively evaluate the technical, functional, and mission effectiveness of C2 processes and services in a complex, hybrid architectural environment. The complexity of that environment arises from the need for legacy C2 systems and newly-developed net-centric processes and services to interoperate in a common environment. The JHU/APL approach uses scenarios to bound the mission space to be evaluated and employs simulation techniques to represent and execute the scenarios with differing levels of fidelity. Simulation types include constructive, virtual, and live simulations. The technical evaluation results obtained from the simulations can be combined with estimated deployment, operations, and maintenance costs to facilitate a combined technical/cost comparison among service offerings from competing portfolios. Thus, this scenario- and simulation-based evaluation approach is expected to help DOD managers make better-informed, best-of-breed decisions regarding which net-centric C2 services should be deployed in an operational environment.

1. INTRODUCTION

1.1 Background

The Department of Defense (DOD) has embarked on a path to make force transformation an integral element of national defense strategy. Transformation is a continuing process involving the evolution of concepts, processes, organizations, and technologies. The term "network-centric warfare" is applied to the combination of emerging and evolving tactics, techniques, and procedures that a networked force can employ to create a warfighting advantage. Network-centric warfare is at the heart of force transformation. Successful transformation hinges on making the right investments in the right area to take full advantage of net-centric warfare and operations technologies and practices. (Garstka and Alberts 2004)

The tenets of net-centric warfare were stated in the DOD's 2001 *Network Centric Warfare Report to Congress*:

- A robustly networked force improves information sharing
- Information sharing and collaboration enhances the quality of information and shared situational awareness
- Shared situational awareness enables collaboration and self synchronization, and enhances sustainability and speed of command
- These in turn dramatically increase mission effectiveness
  (DOD 2001)

> **The evaluation of C2 issues depends in important ways on both distinguishing and linking dimensional parameters, measures of performance, measures of C2 effectiveness, and measures of force and policy effectiveness. Modelling and other tools must be designed to support this requirement.** (NATO 2002, 13-14)

Net-centric command and control (C2) services are intended to help achieve information and decision superiority. Today operations occur in a complex environment characterized by a hybridization of net-centric and more traditional legacy command and control capabilities and processes.

Net-centric transformation and its associated practice of portfolio management require DOD decision-makers to understand the effects various net-centric command and control services have on operational outcomes. Modeling and simulation techniques as described in this paper can be adapted to provide a foundation for assessing net-centric command and control services.

1.2 Purpose

This document describes an approach developed by the Johns Hopkins University Applied Physics Laboratory (JHU/APL) to qualitatively and quantitatively evaluate the technical, functional, and mission effectiveness of command and control processes and services in a complex, hybrid architectural environment where net-centric and legacy capabilities and processes co-exist and must interoperate. This approach uses scenarios to bound the mission space to be evaluated and employs simulation techniques using multiple levels of fidelity or resolution to evaluate net-centric C2 in that complex hybrid environment.

1.3 Scope

This paper focuses on evaluating strategic and national echelons of command and control. The scope of this paper includes a brief discussion of the challenges of net-centric command and control and the goals for evaluating net-centric C2. We describe a framework for conducting that evaluation using multi-resolution modeling (MRM). The paper concludes with a description of a limited C2 evaluation prototype effort (planned for FY05) that will demonstrate how to evaluate smart agent search support for dynamically-created communities of interest.

2. CHALLENGES OF NET-CENTRIC C2

Military operations take place in environments which have legacy elements that are platform-centric and transformed elements that are net-centric. This situation is likely to continue for several years. The contrasts and challenges of this hybrid environment are highlighted in Figure 1.

Legacy Platform-centric:	Net-centric:
» System or systems-of-systems oriented architectures	» Service-oriented architectures
» Stovepipe characteristics; low interoperability	» Core services (net-centric enterprise services)
» Limited standards	» Service interoperability
» Un-tagged data	» Well-defined standards
» More traditional Task, Processing, Exploitation, and Dissemination approach	» Meta-tagged data
» Multi-networked; point-to-point connections	» Defined ontology
	» Information exchange cultural shift (Power to the Edge; Task, Post, Process, and Use)
	» Global Information Grid (GIG)

Figure 1. Command and Control Operations Occur in a Hybrid Environment

Analyzing command and control performance and effectiveness must be accomplished in the context of the entire chain of events in which the C2 activities occur. Modeling and simulation provide techniques to facilitate the evaluation of new C2 services in the context of a realistic operational scenario. The scenario defines parameters to bound the evaluation.

Our hypothesis is that net-centric principles advance C2 capabilities. Testing that hypothesis involves addressing these questions:

- What are the performance bounds and conditions?
- Where is net-centricity appropriate for C2? Where is it inappropriate?
- How does net-centricity affect the strategic and national levels?

The expected outcome is that net-centric C2 is very beneficial in most cases but, perhaps, not in all.

The challenge of evaluating net-centric C2 is:

- To develop an approach to qualitatively and quantitatively evaluate the effectiveness of net-centric C2 processes and services in a complex, hybrid architectural environment, and
- To combine those results with lifecycle costs to facilitate better-informed architecture and technology deployment decisions by C2 portfolio managers.

3. NET-CENTRIC C2 EVALUATION GOALS

Command and control as defined by DOD is

> The exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission. (DOD 2001 as amended through 30 November 2004, 101)

While this definition is still applicable today, the way in which C2 is currently being implemented in a net-centric Global Information Grid (GIG)-enabled environment is quite different from the way it was implemented when this definition was created, and those differences significantly contribute to the complexity of evaluating net-centric C2. For example, prior to the net-centric revolution, C2 was largely achieved via the use of stand-alone, stove-piped legacy systems that communicated with one another via point-to-point network connections. The evaluations of those systems were often limited to demonstrating that the systems met their requirements and were able to effectively communicate with one another over tightly restricted point-to-point connections. Today, or in the near future, commanders employing net-centric C2 implementations will take advantage of distributed computing and communications environments that involve applications developed as services that utilize scalable, service-oriented architectures. Moreover, those net-centric C2 services must interface to some degree with existing legacy C2 systems since the legacy systems can't be replaced by their net-centric equivalents instantaneously.

The complicated hybrid architecture environment and the highly-distributed GIG significantly contribute to the complexity of evaluating and measuring the technical, functional, and mission effectiveness of net-centric C2 processes and services. The goals of the C2 evaluation approach described in this paper must address these additional levels of complexity. Those goals are:

- To demonstrate that a simulation-based methodology is an effective means for evaluating command and control in a hybrid platform-centric and distributed net-centric environment;
- To demonstrate that constructive, virtual, and live simulation techniques can effectively mitigate some of the challenges of evaluation in that hybrid environment;
- In the context of a specific operational scenario,
  - To identify how and where the application of net-centric principles augments the effectiveness of existing C2 capabilities
  - To identify potential gaps where the application of net-centric principles fails to augment or actually degrades C2 capabilities.

4. MULTI-RESOLUTION MODELING (MRM)

4.1 Overview

Simulation is used to construct a microcosm of the capabilities to be studied. The MRM approach uses two or more models of different fidelity or resolution to analyze those capabilities. MRM uses a low-fidelity model to provide analytic agility, efficiency, and understanding to the problem at hand. Often, data may not be available to support high-level simulations when decisions must be made on the value of developing new capabilities. Decisions must be made in the face of significant uncertainties: Will the desired capabilities be achieved? If only a fraction of the estimated improvement is achieved, will the improvement to the C2 process still be worth the investment? Are there other capabilities that would provide a greater improvement with less risk?

Simulation allows us to ask “What if” questions and evaluate quantitative data. A purely constructive simulation (i.e., a model where all aspects of the system are simulated) models the process and allows process changes to be evaluated quickly and easily. One weakness of a constructive simulation is that it is limited by the degree to which the simulated process is a simplified version of the real C2 process.

To reduce this limitation, higher-fidelity simulations such as a virtual simulation are created. Virtual simulations inject “humans-in-the-loop” and can use actual hardware and software as well. Using actual subsystems via a test bed interfaced to the simulation environment removes the simplifications associated with the constructive simulation and results in a higher-fidelity model. The virtual simulation allows for more precise analysis of the real capabilities of the system. Having humans in the loop allows for qualitative assessments to be conducted.

Of course, C2 systems exist to support the interactions of large numbers of warfighters. Live simulations (e.g., exercises or war games) provide significant human-to-human interactions via the C2 process under conditions that emulate combat. Analysis of these events provides insight into how the C2 process would contribute to mission success under real-world conditions.

Each of these analysis components has advantages in terms of cost, time, resources, and fidelity. By combining them in a framework, referred to in this paper as the Multi-resolution Modeling Evaluation Framework (MRMEF), we can achieve effective analysis of C2 processes.

4.2 Simulation Description

Three types of simulations can be used to analyze C2. Each has its own strengths and weaknesses. MRM uses a low-resolution, process-based model to simulate the key activities of the scenario. Higher-fidelity simulations are then used to benchmark the low-fidelity simulation.

4.2.1 Constructive Simulations

Constructive simulations provide the basis for analysis of the C2 process. A simulation tool such as Arena can be used to create a model of the process to be studied. MRM requires a specific approach to building the model. If possible, a hierarchical structure is used so that the model can use a low-fidelity description of the C2 process to do exploratory analysis. The model should also be able to interface with the higher-fidelity hardware and software to simulate specific aspects of the process in higher fidelity.

For example, the time needed to choose a course of action (COA) could be modeled as a simple random variable chosen from an appropriate distribution. Such a function is the lowest-fidelity model of the COA function. Of course, COA times could be described as the sum of several sub-processes: time to receive instructions, time to assemble team, time to collect data, time to formulate initial COAs, time to coordinate and refine COAs, time to approve COAs. Each of these subprocesses could be described as a function of even more variables. Multiple levels of resolution allow the overall model to address issues appropriate to the variables and processes described. A high-resolution model may not allow simple questions to be answered such as "what happens if the opposing forces are better than we expect?" There may be 27 variables that describe the opponent's capabilities, but not one clear and reasonable way to adjust the effectiveness of the opposing forces. Likewise, a low-resolution model is not likely to be able to address the issue of the effect of improved processing speed in the fire control radar of surface-to-air batteries on the outcome of a theater conflict.

To gain an understanding of the impact of key factors in the process, an experimental design is often created and data are gathered on the performance of the system as the factors change. Analysis of the data facilitates development of mathematical models to characterize the response of the system to changes in the key factors. The response functions often illuminate the key issues and identify trade-offs and optimal solutions.

> Valid MRM will often require stochastic variables represented by probability distributions, not merely gross measures such as mean values. Further, valid aggregate models must sometimes reflect correlations among variables that might naively be seen as probabilistically independent. (Davis and Bigelow 1998, x)

"Model-based experimentation has its most obvious utility in support of discovery and hypothesis testing experiments." (Alberts et al. 2002, 319) Reasons for choosing a model-based experiment include:

- Efficiently (in terms of cost and time) exploring a set of scenarios, operational concepts, and technologies….
- Supplementing other experiments…
- Exploring the potential utility of technologies that may not yet exist.
  (Alberts et al. 2002, 319-321)

4.2.2 Virtual Simulations

Virtual simulations allow a high-fidelity component of the system to interact with the lower-fidelity constructive simulation. This component could be hardware, software, or people. Such experiments are often called "hardware-in-the-loop", "software-in-the-loop, or "human-in-the-loop".

Constructive simulations are often done to examine the feasibility of building a system. Once a prototype has been constructed, the actual system can perform its tasks while the rest of the environment is simulated. Such an experiment replaces specified performance parameters with the actual performance of the system under study. Interfaces to the constructive simulation must be developed and used to create the necessary translations from the constructive simulation to the virtual simulation.

MRM allows the low-level model to explore the analysis space and identify interesting regions. These regions can then be explored by creating a detailed scenario in this region and performing analysis with higher-fidelity models to either validate the findings of the lower-fidelity model or to provide feedback to enhance the low-fidelity model so that it is a better representation of the process under study. In C2, human behavior and interactions are notoriously difficult to model and analyze. A key advantage of applying MRM to C2 is that the low-level model provides understanding of the impact of the variables in the C2 process over a wide range of potential values for those variables. The high-level modeling effort can help to identify what the true values of those variables are for specific systems and scenarios.

4.2.3 Live Simulations

> Laboratories and simulations are, however, far less realistic than the settings needed before a transformational innovation should be adopted. Exercises, whether command post (CPX) or field training exercises (FTX), represent the most realistic settings for experimentation and should be employed in the later stages of experimentation campaigns. (Alberts et al. 2002, 55-56)

Accordingly, one part of our multi-resolution evaluation framework employs live simulations to emulate the real-world environment. The real world contains many human-to-human interactions that may not be captured in the lower-fidelity simulations. However, live simulations are expensive, time-consuming, and are difficult (if not impossible) to replicate. A live simulation provides excellent feedback to the constructive model on assumptions, process flows, etc. The outcome of the live simulation should be predicted by the lower-fidelity models. Deviations from the predictions are captured and studied. In this way, each successive level of increasing model fidelity provides the basis for improving the preceding models.

4.2.4 Evaluation Metrics

Experiments are, by nature, empirical. Deciding what to measure is critical to any experiment. The *Code of Best Practices for Experimentation* defines a metric as "the application of a measurement of two or more cases". (Alberts et al. 2002, 155-156)

> In most decisionmaking problems, it is necessary to define several measures that together provide the necessary insights. A major reason for this is that a single measure may not provide sufficient scope and/or detail to analyse the impact of specific C2 elements, particularly second and third order effects or unintended consequences. Many analyses are conducted precisely in order to enable trade-off between important equities which can only be seen if a set of MoM [Measures of Merit] is generated for analysis. The set of MoM selected must be comprehensive to ensure that all factors are considered. (NATO 2002, 94)

Measures of Force Effectiveness (MoFEs) are the ultimate measures of military success or failure. It is the MoFEs that allow trade-offs between disparate capabilities such as more tanks vs. more planes. Is fielding the latest generation fighter more advantageous than improving the C2 system? The behaviors of the entities in question can be measured and are considered Measures of Performance (MoPs). "How fast?", "How far?", "How accurate?", "How often?", etc., are the types of questions measured by MoPs. Measures of Effectiveness (MoEs) estimate the impact of the system under study (and its associated MoPs) with measures of mission effectiveness such as number of days to establish air supremacy, blue/red kill ratios, etc.

In MRM, one important task for creating higher-resolution models is to characterize the behaviors to be modeled as stochastic variables in the low-resolution model. If the mean and variance of such stochastic variables are not close in value to the true values of the underlying process, then the results of the low-level model may be inaccurate, particularly, if one or more of those stochastic variables contributed significantly to the overall outcome of the mission. One of the primary functions of the higher-resolution model is to validate the lower-resolution model.

4.3 Assess Cost and Options

Once MoFEs have been measured, lifecycle costs can be analyzed to illuminate the cost-benefit trade-offs. Figure 2 shows an example of what such a cost-benefit analysis might look like. Imagine six possible portfolios of C2 systems. The total lifecycle cost of each portfolio has been estimated and the MoFE used for this analysis is the probability of mission failure, which is plotted on the horizontal axis.

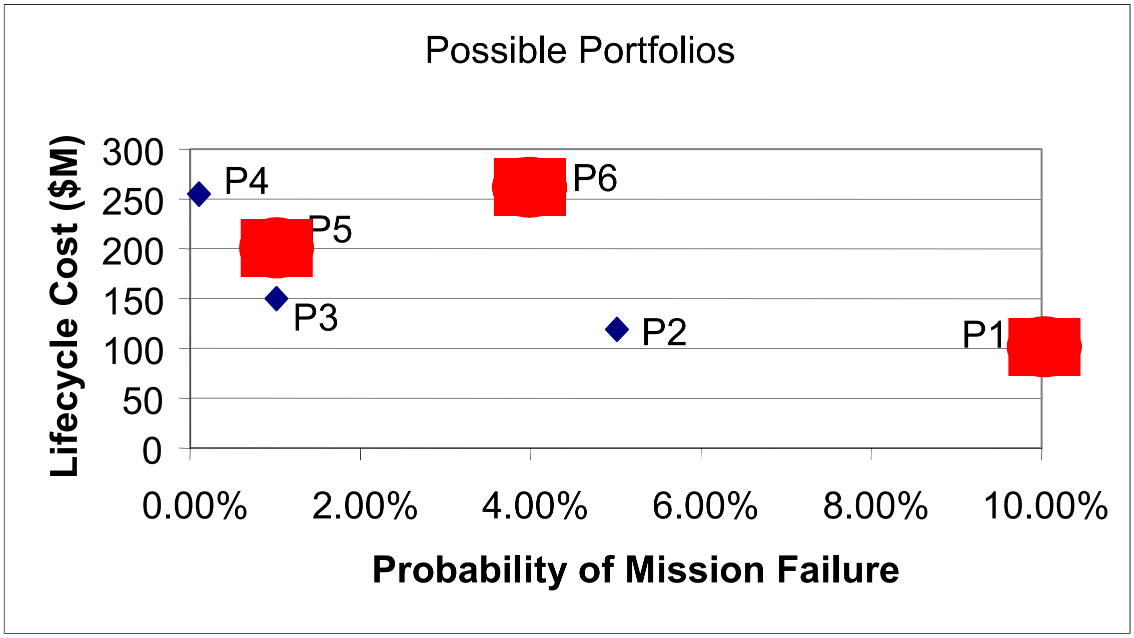

Figure 2. Example of a Cost-Benefit Trade-off Analysis

In this type of multi-criteria decision-making, a single optimal answer doesn't exist unless the value in dollars is known for reducing the chance of mission failure by one percent. For example, if mission failure implied an extended operation at the cost of $1B, then the "value" of reducing the probability of mission failure by 1% is estimated to be $10M. Among the possible portfolios shown above, P3 is estimated to cost $150M to implement and deploy and has a 99% chance of mission success, or, alternatively, a 1% chance of mission failure. If that 1% risk is deemed acceptable, then selecting P3 would be the best choice. Further reducing the risk to approximately 0% by selecting P4 would not be cost effective because the cost of implementing and deploying P4, i.e., $250M, would exceed the estimated cost of a 1% reduction in mission failure by a factor of 10. Some portfolios can be identified as poor choices: P1 is inferior to P2 because it has twice the chance of mission failure at approximately the same cost. Both P5 and P6 are inferior to P3 because they cost more and have equivalent or higher risk. Portfolios P2, P3, and P4 each represent reasonable choices, i.e., they lie along the "efficient frontier". A decision-maker's preference among these three depends upon how much risk is considered acceptable and how much funding is available to achieve that level of risk.

5. MRM EVALUATION FRAMEWORK (MRMEF) APPROACH

5.1 Description

A significant challenge to evaluating net-centric C2 is to develop an approach that facilitates evaluation of C2 capabilities in a complex hybrid architecture environment. Our approach, referred to as the Multi-resolution Modeling Evaluation Framework (MRMEF), uses constructive, virtual, and live simulations and hardware-, software-, and humans-in-the-loop where appropriate. Multi-resolution Modeling (MRM) has many advantages that are needed to analyze C2. MRM has been successful because it has the characteristics needed to solve difficult analysis problems by integrating information achieved with high-fidelity models and generalizing the results and implications via a low-resolution model (Smith 1998). An overview of the MRMEF is shown in Figure 3.

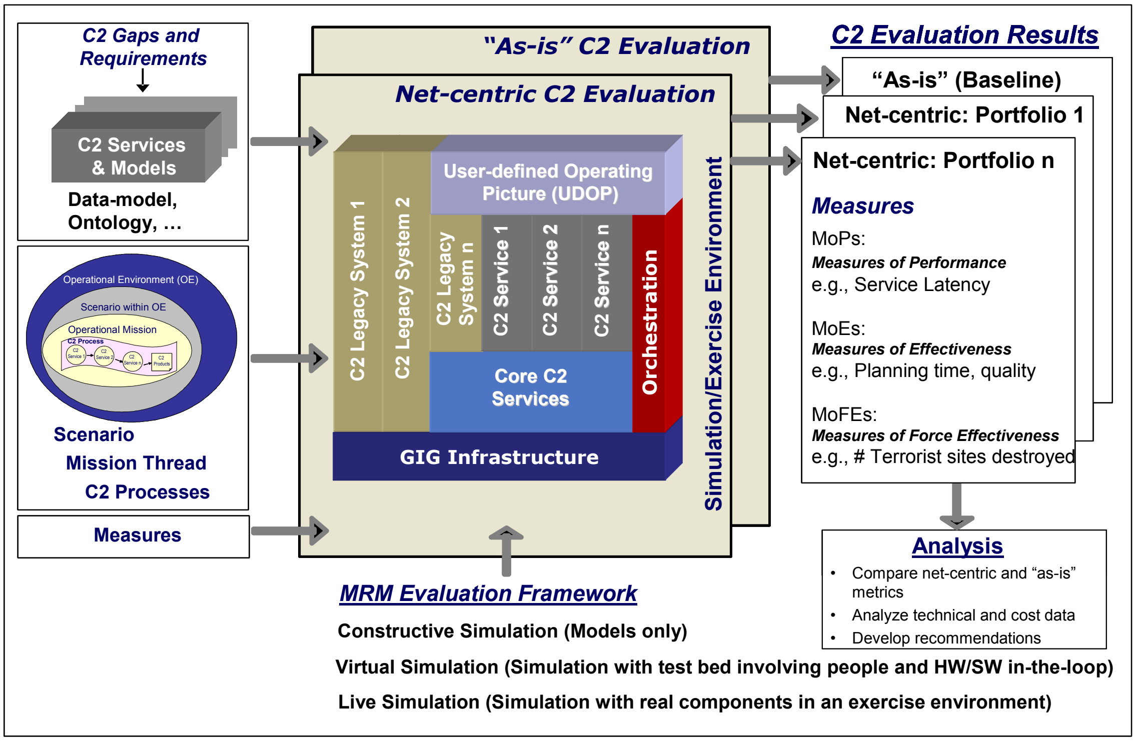

Figure 3. Multi-resolution Modeling Evaluation Framework

The simulation/exercise environment of the MRMEF contains the entire hardware and software infrastructure needed to support the constructive, virtual, and live simulations of the framework.

The "cube" portion of the diagram represents real or modeled C2 or C2-related components. Inputs to the framework consist of a set of C2 services to be evaluated; the services were derived from C2 gap analysis, C2 requirements definition, data modeling, and so forth. A scenario defines the operational mission, i.e., the problem to be solved, and serves as the contextual basis for the evaluation. Measures to assess performance and effectiveness are defined based on the context of the scenario. Evaluation of C2 capabilities is accomplished by executing the "cube" components, (real, simulated, or a combination of real and simulated) in the context of the appropriate MRMEF simulation/exercise environment. C2 evaluation results are generated as a result of executing the scenario.

An "as-is" evaluation is accomplished by developing a scenario-based model of the "as-is" process to be evaluated and executing that model as a constructive simulation within the framework. A second model is developed representing the net-centric equivalent of that process.

The net-centric process, which may involve a hybrid of legacy and net-centric components, both real and simulated, is executed within the framework as a virtual simulation. When real components are used, they are interfaced with the simulation via a separate test bed, which allows the real components to interact as necessary with modeled components. The resulting simulation executes at a higher level of fidelity or resolution overall. The framework also encompasses a very high-fidelity live simulation executed outside the laboratory environment with real players and components.

Analysis consists of comparing the "net-centric" with the "as-is" results and analyzing the differences to determine, both qualitatively and quantitatively, whether the application of net-centric principles and components to an existing process has enhanced or degraded engineering, command and control, or mission-level performance as measured via MoPs, MoEs, and MoFEs, respectively. If cost information about deploying and maintaining net-centric C2 capabilities is available or estimated, those data can be combined with the technical evaluation results to help guide future architecture, acquisition, and deployment decisions.

The steps to evaluate a proposed net-centric enhancement to C2 processes are summarized below:

Step 0: **Identify Components**. Inventory the elements to be evaluated, models, datasets, and other data and tools to be used.

Step 1: **Define Scenarios and Metrics**. Develop or leverage upon existing scenarios to bound the evaluation problem and, within that context, develop a set of metrics to measure the performance of the net-centric C2 services to be evaluated.

Step 2: **Evaluate via Laboratory Simulation.** Bounded by the scenario, evaluate C2 processes and net-centric services via modeling and simulation (constructive and virtual). Evaluate both the proposed net-centric and as-is versions of the processes. Different models may be required.

Step 3: **Evaluate via Live Simulation**. Deploy and evaluate net-centric services from one or more portfolios via live simulation in an exercise/experimentation environment. Live simulation is likely to be used to focus on the proposed net-centric enhancements.

Step 4: **Assess Costs and Options.** Combine technical evaluation results with expected deployment and operations and maintenance costs for each portfolio; compare portfolio offerings.

5.2 MRMEF Prototype

We plan to validate the MRMEF concepts by constructing an evaluation prototype for selected C2 capabilities. Specifically, we will demonstrate how to evaluate smart agent search capabilities in the context of providing information provisioning support to dynamic operational communities of interest (DOCOI) collaboration sessions. By demonstrating that evaluation capability, we will propose how the MRMEF could be directly extensible to the evaluation of other existing and future net-centric C2 capabilities.

5.2.1 Prototype Objectives

The objectives of this prototype effort are to:

- Demonstrate how the MRMEF is used to evaluate smart agent search capabilities for DOCOI collaboration
- Show, through example, how the MRMEF could be directly extensible to the evaluation of other future and existing net-centric C2 capabilities

5.3 Prototype Approach

The approach for the MRMEF prototype involves:

- Developing or utilizing an existing scenario in which DOCOIs are responsible for developing courses of action to accomplish the mission. Figure 4 shows a sample high-level scenario. The scenario includes developing COAs for integrated missile defense in response to terrorists acquiring a weapon of mass destruction (WMD) and potentially attempting to launch it.

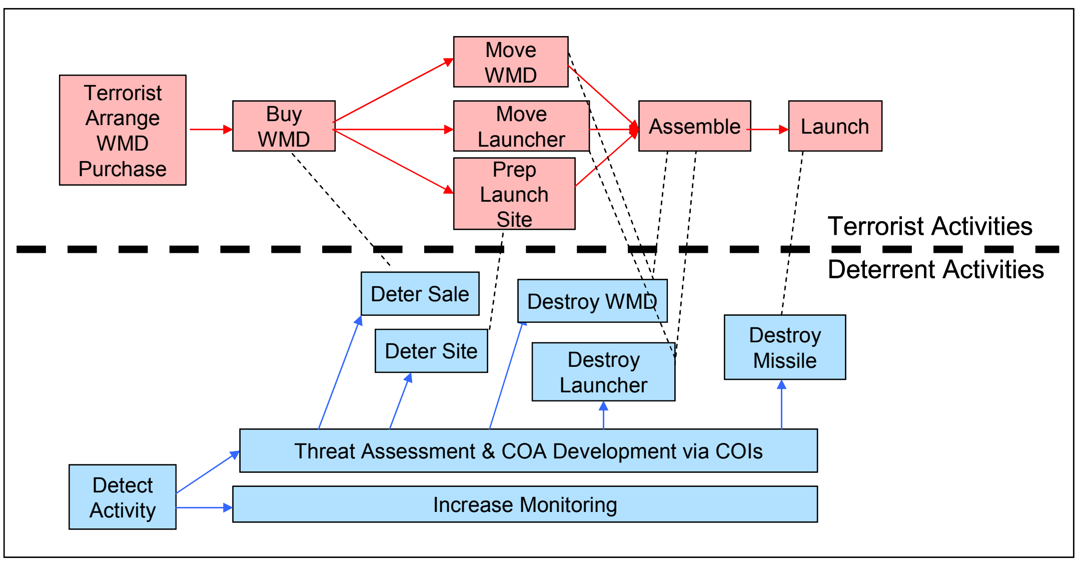

Figure 4. Sample Integrated Missile Defense Scenario

- Developing a set of metrics to evaluate the performance of the DOCOIs and the supporting smart agent search capabilities. Metrics might include assessment of the kinds of participants included in the DOCOI, their role-based access levels, their level of understanding of the information provided, and the extent to which understanding was aligned across the DOCOI.
- Developing a low-fidelity simulation to characterize the current (as-is) C2 collaboration processes in the context of the scenario. Measure performance via the metrics defined above using a simulation tool such as Arena.
- Developing a second simulation to characterize C2 collaboration processes in a net-centric DOCOI environment augmented by smart agent search capabilities. Measure

performance via the metrics defined above in a simulation environment that includes the real smart agent service integrated with legacy system software components, where appropriate.

- Comparing the results of the two simulations to obtain a qualitative and quantitative assessment of the smart agent search capabilities as they support net-centric C2 DOCOI collaboration performance.

5.3.1 Prototype Assumptions and Constraints

Although the MRMEF is intended to support cost analysis as well as performance and effectiveness evaluation, that function will not be included in the FY05 prototype effort. The cost analysis capability is expected to be evaluated in FY06.

6. CONCLUSIONS

As net-centric C2 services are being developed in the context of service-oriented architectures and deployed in the field to support real-world operations, there is an absolute need to ensure these services operate properly in both a unitary mode and in end-to-end orchestrations with other services and systems. The benefits of applying a multi-resolution modeling approach as described in this paper to the complex problem of evaluating services and legacy systems that need to interoperate with each other in order to facilitate effective C2 are:

- Reduced deployment risks;
- Better informed architectural and deployment decisions by DOD managers;
- Increased return on investment via reduced operations and maintenance costs;
- Enhanced best-of-breed selection among competing portfolio capabilities;
- Improved techniques, tactics, and procedures and concepts of operations via in-the-loop resource experimentation; and
- Synergism with the Joint C4I Program Assessment and Joint Interoperability Test Command Testing and Certification Processes.

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8. ACRONYMS AND ABBREVIATIONS

C2	Command and Control
C4I	Command, Control, Communications, Computers, and Intelligence
CCRP	Command and Control Research Program
COA	Course of Action
COI	Community of Interest
CPX	Command Post Exercise
DOCOI	Dynamic Operational Community of Interest
DOD	Department of Defense
FTX	Field Test Exercise
FY	Fiscal Year
GIG	Global Information Grid
HW	Hardware
JHU/APL	Johns Hopkins University Applied Physics Laboratory
MoE	Measure of Effectiveness
MoFE	Measure of Force Effectiveness
MoM	Measure of Merit
MoP	Measure of Performance
MRM	Multi-resolution Modeling
MRMEF	Multi-resolution Modeling Evaluation Framework
NATO	North Atlantic Treaty Organisation
OE	Operational Environment
SW	Software
UDOP	User-defined Operating Picture