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Promoting Affordability in Defense Acquisitions: A Multi-Period Portfolio Approach

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Panel 17. Predicting Performance and Interdependencies in Major Defense Acquisition Programs

Thursday, May 15, 2014	
1:45 p.m. – 3:15 p.m.	**Chair: Nancy L. Spruill,** Director, Acquisition Resources & Analysis, Office of the Under Secretary of Defense (Acquisition, Technology, & Logistics) ***A Scalable Approach to Modeling Cascading Risk in the MDAP Network*** Anita Raja, University of North Carolina Charlotte Mohammad Hasan, University of North Carolina Charlotte Shalini Rajanna, University of North Carolina Charlotte Ansaf Salleb-Aouissi, University of North Carolina Charlotte ***Promoting Affordability in Defense Acquisitions: A Multi-Period Portfolio Approach*** Navindran Davendralingam, Purdue University Daniel DeLaurentis, Purdue University ***Lexical Link Analysis Application: Improving Web Service to Acquisition Visibility Portal Phase II*** Ying Zhao, Naval Postgraduate School Shelley Gallup, Naval Postgraduate School Douglas MacKinnon, Naval Postgraduate School

Promoting Affordability in Defense Acquisitions: A Multi-Period Portfolio Approach

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Abstract

The implementation of Better Buying Power policies seeks to achieve affordability across the spectrum of major defense acquisition programs. However, the technical and programmatic challenges associated with sequential decision-making in the acquisition of large scale, increasingly interdependent defense systems prompts a need for quantitative frameworks that can better address the complexities of negotiating capability, schedule, and cost, while fulfilling target objectives of affordability. Our proposed research extends prior funded work and adopts innovations from financial engineering to enable quantitatively informed multi-stage decision-making under uncertainty. The method provides a means of assessing tradeoffs between capability, cost, and schedule risks, and the ability to objectively make sequentially dependent acquisition decisions on a "portfolio" of systems, towards some desired overarching capability. We adopt a dynamic programming approach using statistical measures and optimization techniques that balance short term decisions against long term implications on dimensions of cost, risk, and schedule. The method is demonstrated for the concept case of multi-stage acquisitions in a naval acquisition scenario.

Introduction

The U.S. Department of Defense (DoD) has emphasized a need for Better Buying Power (BBP) initiatives in tackling issues of increasing costs, schedule growth and programmatic failures. Dr. Ashton Carter, under secretary of defense for acquisitions, technology and logistics, in a series of memo issues, has called for a need for "Should Cost" policies to promote affordability in defense acquisitions. "Should Cost" policies involve a practical approach to reducing costs of defense portfolios through targeting of cost growths, incentivizing productivity and innovation, reducing redundant processes, promotion of real competition and improvement of tradecraft in acquisition of services. The spirit of the move towards affordability is to promote the identification and acquisition of sensible technologies (or programs) at an acceptable cost and at minimum schedule risk. Policy levers (e.g., incentivized contracting) are used to promote innovation, while at the same time, reducing cost growths and redundancies in the capabilities of the warfighter portfolio. The reduction in technical and programmatic redundancies is in line with the U.S. military's vision of promoting adaptability and resilience in capabilities where systems and assets can adapt, through reconnections and redeployment of existing assets, towards meeting the needs of a changing warfighter scenario.

Additionally, there have been significant efforts in promoting competitive innovation through Open Architecture (OA) and rapid prototyping initiatives. OA establishes set standards that enable the leveraging of technological innovations, with emphasis on Small Business Innovation research (SBIR) and Small Business Technology Transfer (STTR) mechanisms that can readily interface with existing platforms, based on set interface standards. More specifically, OA involves the design and implementation of systems that conform to a common and unified set of technical interfaces and business standards. This form of "open architecture" tests and broadens potential innovations to a much larger scope than traditional acquisition processes. Rapid prototyping complements efforts such as the OA to enable rapid proof-of-concept testing and fielding in warfighter test environments. Rapid prototyping and testing of new, yet-to-be introduced systems naturally provides objective information on the potential operational value of individual systems early on in the platform lifecycle.

The current needs of the U.S. military still challenges the effectiveness of BBP policies in acquiring "capabilities" rather than localized acquisition of an individual system. The acquisition of "capabilities," through Major Defense Acquisition Programs (MDAPs), presents unique complexities that exist between yet-to-be acquired and existing system capabilities. BBP policies, OA and rapid prototyping are examples of policies that serve to determine the value of yet-to-be introduced systems. However, these serve as general guidelines and cannot deal with the technical and programmatic complexities of the overarching collection of systems or "system of systems" as a whole that contribute collectively to a desired capability. Furthermore, the decision-spaces associated with evaluating the connectivity, capabilities and development schedule impacts under uncertainty, can involve a large number of variables that can often go beyond the immediate mental faculties of the decision-maker. The problem in size of the decision space exacerbates the difficulty of decision-making in situations where early on acquisition decisions can have an impact on subsequent decision-epochs of an acquisition strategy. The current guidelines in the DoD Acquisitions Guidebook (DAG), and the DoD System of Systems Engineering (SoSE) Guidebook do not provide distinct methodologies in managing the quantitative complexities that can manifest across technical and programmatic dimensions of development. The need for necessary quantitative tools in support of evolving the U.S. military's desired portfolio of capabilities, while negotiating the dimensions of cost, risk and schedule in a multi-epoch setting, motivates our body of research.

Affordability: An Investment Portfolio Perspective

Affordability is not a static notion—the tenets of affordability demand a constant enforcement of policies throughout the evolutionary path of developing defense capabilities and requires that selection of investments be made based on what is deemed as sensible. Here, sensible more specifically refers to identifying investments in programs/systems that justify theirs risks and can achieve the capabilities required based on the finite boundaries of allocated budget. The sequential nature of decision-making, in the management of MDAPs, bears much semblance to the practice of the multi-period portfolio problem in finance where portfolio managers sequentially adjust the positions of their highly populated portfolios, in an effort of maximizing profit, under conditions of market uncertainty. The financial portfolios are subject to market uncertainties, transaction costs of portfolio adjustments, and constrained by various investment rules that dictate compatibility policies, risk limits and capital limits as well. Portfolio management techniques have been employed in the strategic management of military acquisitions. Prior works include application of Real Options (RO) theory (Giachetti, 2012; Mun, 2005) to map potential investment options as distinct branches of a decision-tree. Work by (Giachetti, 2012) has adopted a real options framework that utilizes stochastic techniques to managing military investments. Work by (Mun, 2005) establishes an eight phase process to addressing portfolio management of strategic assets and has been applied in corporate environments. Prior research, funded by the Naval Postgraduate School (NPS) and presented at the 2012 NPS Acquisition Research Symposium (Davendralingam, 2012), has focused on a robust portfolio management problem of maximizing a warfighter system of systems portfolio performance index while preserving budgetary and compatibility constraints of underlying military assets. Risks and capabilities stemming from inter-system interdependencies span the functional and physical spaces of the system of systems architecture. The developed strategy supports acquisitions, both in the pre- and post- milestone B phases in improving affordability and BBP objectives while considering evolving military requirements.

The work has been subsequently extended (Davendralingam, 2013) to a multi-stage robust portfolio management problem in which a warfighter performance index for a large collection of systems or “System of Systems (SoS),” is maximized while leveraging the potential gains in overall SoS capability against cost and developmental risks in selecting “baskets” of functionally and physically compatible, interdependent systems. The method utilizes robust optimization techniques developed by Bertsimas (Bertsimas, 2004, 2008) to address correlated data uncertainties that may exist over the strategic horizon. However, the implementation only considers static correlation over the entire strategic horizon—a notion that may be very difficult to accurately ascertain, and may not yield insights in tactical aspects in defense acquisition decision-making.

Our current research extends this framework to include a more tactically effective representation of system level objectives (and constraints) that are reflective of cost, capability and schedule, within a dynamic optimization framework. The representation can better capture investment issues such as deciding between building upon legacy architectures or developing new ones, consideration for reduced costs due to competition effects, and leveraging advantages from open architecture policies. Additionally, the method includes statistical measure updates that reflect transitional risks, and consequent dependencies that acquisitions decisions have on propagating risks. Our framework seeks to reduce the complexities associated with the large dimensional tradespace of managing portfolios of systems to a more manageable set of adjustable performance/risk driven parameters within the context of a computational acquisitions support tool.

Evolving Capabilities in Defence Acquisitions

Military capabilities arise out of the hierarchical structure of translating localized capabilities of interconnected systems, to the metrics of what constitutes a suite of overarching capabilities. Figure 1 illustrates this hierarchical arrangement of systems that collectively constitute a system of systems architecture. Here, systems that serve at various levels of operational hierarchy (from α to ϒ level) are in turn, operationally connected to other systems that may come under control of different managerial authorities. The cooperative dynamics of these masses of systems, in turn satisfy requirements (such as ability to execute mission threads and achieve defined capabilities) that translate to the capability of the system of systems architecture as a whole. Changes (adding, removing, upgrading, retiring, etc.) of individual systems can potentially lead to either beneficial or deleterious repercussions on the overall system of systems as a whole, and is therefore dependent on judicious execution of proposed changes. These changes are regularly executed in piece meal fashion (localized) with minimal consideration to the systems of systems as a whole; the localization is in part due to the absence of technical decision-making frameworks that can better assist acquisition practitioners in making better informed decision on acquisitions, and their impact on the picture as a whole.

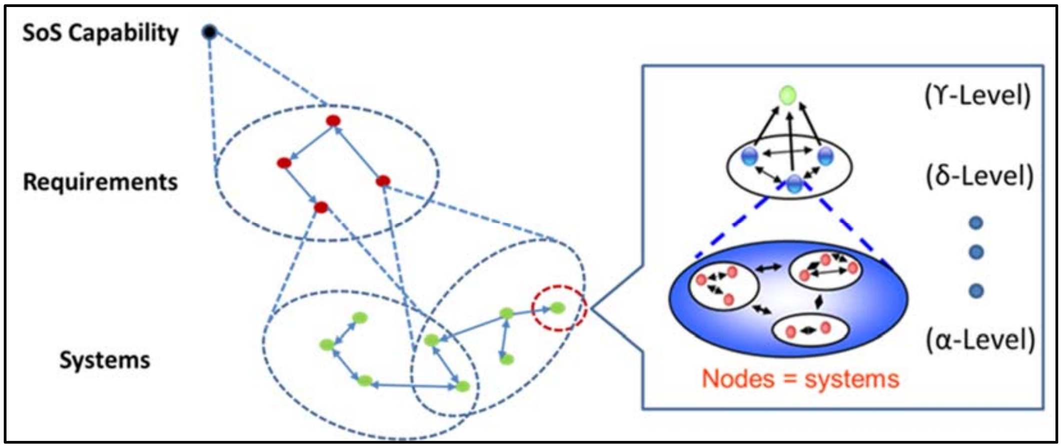

Figure 1. Hierarchy and Transition of Systems to System of Systems (SoS) Capabilities

Figure 2 is an abstraction of the evolutionary aspects of a “portfolio of systems,” and is captured through the *Wave model* (Dahmann, 2011). The *Wave model* extends the Department of Defense guidelines on systems engineering (SE) for a system of systems (SoS) that translates SoS SE core elements, interrelationships and decision-making artifacts from a previous “Trapeze” model to a time sequenced model representation (Dahmann, 2011).

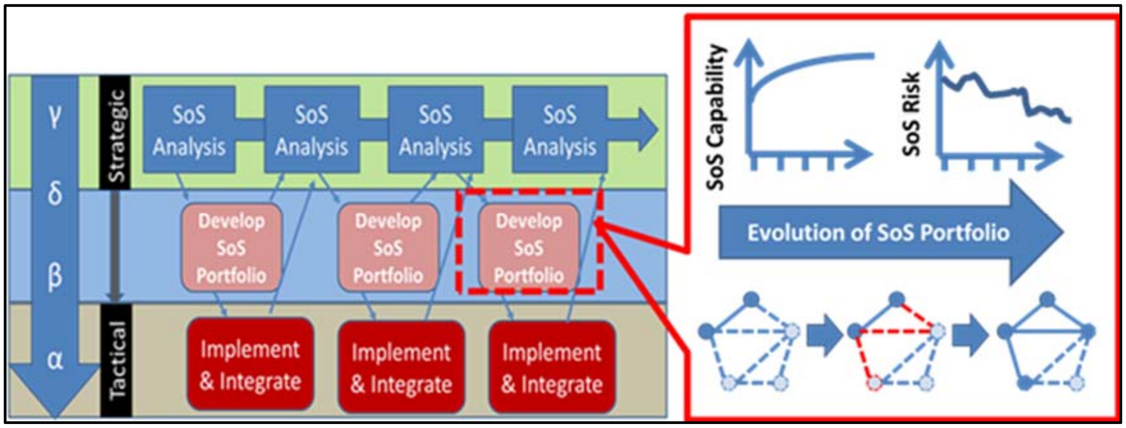

Figure 2. Wave Model Relation to Portfolio Evolution

These architectural evolutions involve acquisition based decisions (add, remove, etc.) on assets, towards meeting core objectives. The practitioner’s role is therefore to explore the trade space across multiple operationally independent domains, and perform necessary acquisition decisions that support desired capability objectives while limiting cost to a prescribed finite budget, assessing feasibility of development schedule and limiting foreseeable risks.

The objective of the multi-period portfolio framework in our research is to allow for mathematical rigor of algorithmic techniques (transparent to the end user/acquisition practitioner), to support acquisition decisions through identification of optimal “portfolios” and acquisition policies in pursuit of desired capabilities. While the acquisition process spans operationally and managerially independent defense groups, the tools and frameworks envisioned to support these aspects are aimed at providing adequate quantitative support of trades-pace insights. These explorations require a domain agnostic framework, and hence intuitively resonate with the idea of treating the collection of systems across domains as a “portfolio” of systems. Our work extends the prior robust formulation to also yield more tactical acquisition insights at each decision epoch of acquisitions.

Developing a Multi-Period Strategy With Tactical Updates

Acquisition decisions on existing and yet-to-be introduced systems, in an evolving a system of systems, inherently involves a timeline of sequentially executed decisions. We enforce a representative, domain independent model that describes node (system) attributes. These attributes reflect feasibility of constructed portfolios with respect to technical and programmatic constraints. Figure 3 shows modeled generic behaviors for systems being considered in a system of systems portfolio (Davendralingam, 2013).

System of Systems Modelling

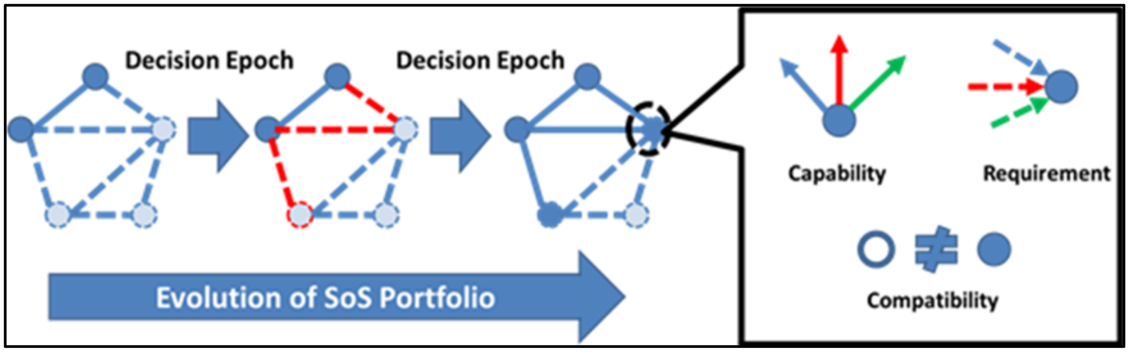

Figure 3. **Archetypal Node (System) Behaviors**

In Figure 3, the capabilities of an existing system of systems (initial blue nodes), have the potential to evolve, based on potential connections to yet-to-be acquired systems (dashed lines and nodes). At each decision epoch, the practitioner utilizes a decision-making framework to evaluate the value and risks involved in the potential acquisitions of new systems (denoted by red dashed lines). Evaluation of such information can potentially come from prototyping/test and fielding results, or other such information seeking/risk reducing acquisition actions. The resulting new collection of systems that comprise the new portfolio, now include the addition of the new systems and identifies appropriate decision-paths that are necessary to achieve the target collection of systems. Our current research explores the incorporation of tactical information at each update, to enable subsequent epoch decision-analysis using the portfolio based framework. The work enforces constraints on system selection where each system is treated as a generic discrete node with the following attributes:

- *Capability* (Outputs): Nodes have finite supply of transmittable capabilities
- *Requirements* (Inputs): Nodes have internal requirements that can be fulfilled by connecting to other nodes that can provide for the need.
- *Compatibility*: Nodes can connect to other nodes based on specific combinatorial rules.

The *capabilities* and *requirements* relationship between nodes can be binary in nature (yes/no) or reflect some numerical quantity between them. Additionally, there can be uncertainty in the quantified values, as is the case, for example, in acquisitions of systems with lower TRL numbers.

Investment Portfolio Formulation

The acquisition problem is expressed as a mathematical programming problem. The process begins with the definition of two main elements of a mathematical program, namely, the *objective function* and *constraints*. The objective function reflects key performance metrics of the system to be maximized (or minimized). For a system of systems, the objective function reflects a chosen measure of performance. The second important aspect of a mathematical program is the formulation of the constraints. The constraints reflect physical, resource and behavioral aspects of the systems as mathematical expressions. Our preliminary framework for a multi-period portfolio considers a long term horizon of acquisitions with discrete decision epochs that reflect investment decisions. These decisions can involve acquisition actions such as the addition/removal of individual systems towards achieving a desired capability.

The following mathematical program describes a preliminary framework towards the overall portfolio acquisition problem:

$$\max\left(\sum_{q}\left(\frac{S_{qc}-R_c}{R_c}\cdot w\cdot x_q^{t=T}\right)\right) \tag{1}$$

Subject to:

$$\sum_{q} S_{qc}x_q \geq \sum_{q} S_{qR}x_q \quad \text{(Satisfying each type (c) requirement)} \tag{2}$$

$$(x_i+..+x_n)_j = M_j \;\; \text{j=1…k} \quad \text{(package system compatibility)} \tag{3}$$

$$\sum_{q=1}^{n} Cost_q x_q + Cost_{q\in TRL<8}^{\text{Research}} x_q \leq \text{Budget} \tag{4}$$

$$Mx_q - TRL_q x_q \leq 0 \tag{5}$$

$$TRL_q x_q - Mx_q \leq 0 \tag{6}$$

$$x_q \in [0,1],\; x_q^{TRL} \in [0,8]$$

$$TRL_{q\in TRL<8},\; Cost_{q\in TRL<8} \;\text{(Uncertain)}$$

Equation 1 is the weighted objective function that seeks to maximize the end developed portfolio performance index. Here, the index is weighted according to the normalized value that each capability (C) contributes to the index. The normalization is performed with reference to some minimum acceptable performance value for each capability, R_c. Equation 2 ensures that the total "capabilities" from selected systems are able to satisfy the requirements of connected systems that are in need of a particular capability. For example, there must be adequate communications bandwidth capability stemming from the selected communications assets, so as to enable performance of the weapons systems for the same naval asset. Equation 3 enforces compatibility constraints as binary conditions for a total of (*k*) set of rules; for example, the constraint that only one engine can be selected to generate power would translate to a constraint of $x_1 + x_2 = 1$ where (x_1, x_2) are binary variables. Equation 4 ensures that the costs of developing (in this case, the cost of promoting, via research, low Technology Readiness Level (TRL) technologies to an acceptable fielding level of TRL 8) and cost of acquisition are within a prescribed budget;

this is in line with the notion of affordability where finite resources are considered. Equations 5 and 6 utilize a linear programming structure known as a Big-M approach to establish a logical expression; here the systems selected for the end deployment can only be of TRL level 8 and above.

Equations 1–6 constitute the overarching investment problem where the objective is to select and end portfolio that maximizes a warfighter portfolio performance index (objective function) while preserving budget and feasibility constraints on the readiness of technologies that need to enter to the final portfolio. The final acquisition costs of yet-to-be introduced systems below a TRL level 8 and the final TRL status (TRL_q) of researched systems are considered to be uncertain. These uncertainties intuitively have correlated properties as the development of technologies for interconnected systems, would likely benefit in some cooperative sense. We also assume that the TRLs and costs evolve as a product of research investment due to defense interests—this investment guided evolution is in line with current practices of proof of concept and rapid prototyping of potential technologies and services at various TRL levels.

Dynamic Programming Overview

The investment portfolio problem of Equations 1–6 is reflective of the need to maximize the end portfolio capabilities of a collection of systems that are governed by behavioural rules of connectivity and influenced by data uncertainty. Our prior multi-period portfolio work has approached the problem within the context of a robust optimization problem that utilized innovations in robust (correlated data) linear programming techniques (Bertsimas, 2004); the application of the method, however, is strategic in nature and depends on static correlations—a notion that may not hold true in dynamic defence acquisition environments. While the robust portfolio framework offers useful insights, there is nevertheless a need for a dynamic framework that can provide useful tactical timeline decision-making support, and, possess good long-term evolutionary performance.

Acquisition decisions in earlier epochs typically have a cascading implications on the performance and risks in subsequent decisions; this form of a problem has long been address under the premise of *dynamic programming*. Dynamic programming has evolved out of many areas of research, ranging from economics to modern control theory (Powell, 2011). The general form of a dynamic programming problem can be written as the following:

$$V_t(S_t) = \max_{x_t} C_t\,(S_t, x_t) + V_{t+1}(S_{t+1}) \tag{7}$$

$$V_t(S_t) = \max_{t=0}\{\gamma^t C_t^{\pi}(S_t, x_t^{\pi}(S_t))\} \tag{8}$$

where C_t() is the reward function of current time step

S_t is the current state

x_t is the action taken at time (T)

V_t+1 is the value function of being in state S_t+1

Υ is a weighting constant, π is a set of all policies

Equations 7 and 8 are the deterministic and stochastic representations of the Hamilton-Jacobi-Bellman (HJB) equations. Typically, these are solved using backward recursion, over all possible states and seek a sequence of decisions (x_t) that maximize (or minimize) an objective function. The value of the objective is dictated by being in particular states (S_t) (here, a state, in the context of our acquisition problem, may be the overarching military value of current holdings of systems and their potential connections to future systems). The traditional means of solving these equations backward in time can prove to be extremely expensive/difficult due to many reasons that include computational intractability (also known as the *curse of dimensionality*), absence of models for future states and dependency on data that does not yet exist. An alternative, and highly attractive practice in dealing with these kind of problems involves the use of Approximate Dynamic Programming (ADP) approach that essentially solve the problem in a *forward* dynamic programing approach (Powell, 2012; Bertsekas, 2011). In the context of a defence acquisition scenario, this is highly intuitive given that the structure of testing, prototyping, simulation, and so forth, presents new information in a forward sense, to help inform decision-makers in adjusting their portfolios of systems. Our research complements this *forward* view with our multi-period portfolio approach, using an ADP inspired methodology.

Multi-Period Portfolio Optimization

We formulate the investment portfolio problem (with uncertainty in TRL and cost) of Equations 1–6 as a forward dynamic programming problem where the objective is to sequentially update acquisition decisions as TRL and cost of potential, yet-to-be introduced system evolve over a discretized finite horizon. The resulting forward dynamic programming problem is then stated as

$$\max\ \mathrm{E}\left(\sum_{q}\left(\frac{S_{qc}-R_c}{R_c}\cdot w\cdot x_{q,t}^{TRL>8}\right)+\gamma\left(\frac{S_{qc}-R_c}{R_c}\cdot w\cdot x_{q,t}^{p}\right)\right) \tag{9}$$

Subject to:

$$\sum_{q} S_{qc}x_{q,t}^{p} \geq \sum_{q} S_{qR}x_{q,t}^{p} \quad \text{(Satisfying each type (c) requirement)} \tag{10}$$

$$\left(x_i^p + .. + x_n^p\right)_j = M_j \ \mathrm{j} = 1 \ldots \mathrm{k} \quad \text{(package system compatibility)} \tag{11}$$

$$\sum_{q=1}^{n} Cost_q x_{q,t}^{TRL>8} + Cost_{q\in TRL<8}^{\mathrm{R}} x_{q,t}^{R} \leq \mathrm{Budget}_t \tag{12}$$

$$\sum_{q=1}^{n} Cost_q x_{q,t}^{p} \leq \mathrm{Budget}_{t=T} \tag{13}$$

$$Mx_{q,t}^{TRL>8} - TRL_{q,t}x_{q,t}^{P} \leq 0 \tag{14}$$

$$TRL_{q,t}x_{q,t}^{P} - Mx_{q,t}^{TRL>8} \leq 0 \tag{15}$$

$$x_{q,t}^{R} = x_{q}^{P} - x_{q,t}^{TRL>8} \tag{16}$$

$$x_{q,t}^{TRL>8}, x_{q,t}^{p}, x_{q,t}^{R} \in [0,1], x_{q}^{TRL} \in [0,8]$$

where:

$x_{q,t}^{TRL>8}$ Decision variable to acquire in system (q) at time (t)

$x_{q,t}^{p}$ Total portfolio of systems (q) at time (t) based on current value of capabilities

$x_{q,t}^{R}$ Decision variable to invest in research for systems below TRL 8 (q) at time (t)

Υ discount term/belief term

Equations 9 is the objective function that now seeks to balance the potential gains from investing in ready technologies at the current decision epoch, through investment decision variable ($x_{q,t}^{TRL>8}$), against the potential for future value in the overall portfolio of capabilities based on the decision variable (x_q^p); note that the contribution of the potential future value is dependent on the maturity of a TRL level to exceed level 8. Equation 10 enforces that system requirements of the end potential portfolio of systems are satisfied by capabilities from other connected systems. Equation 11 enforces compatibility constraints. Equation 12 ensures that combined piece-wise acquisitions of costs at the current decision-epoch, and the cost of researching technologies below TRL 8. Equation 13 enforces the long-term budget satisfaction of the projected portfolio of systems. Equations 14–15 ensure that only TRL>8 systems can be acquired at each decision-epoch. Equation 16 establishes the relationship between decision-variables where decisions to research certain systems ($x_{q,t}^{R}$) and acquire mature ones ($x_{q,t}^{TRL>8}$) comprise the overall projected end portfolio of systems (x_q^P) at the final decision epoch. The optimization problem of Equations 9–13 constitute a Binary Integer Program (BIP) and was modeled using YALMIP (Löfberg, 2004) within the MATLAB environment (MATLAB 2010), using the Gurobi Optimizer (Gurobi Optimization, Inc. 2004), solver option. The optimization problem of Equations 9–13 is solved recursively over each investment decision epoch. At the end of each epoch, TRLs (and cost) of yet-to-be introduced systems are evolved to a new estimate, based on the prior epoch's investment decision ($x_{q,t}^{R}$) in relevant technology.

Concept Application: Naval Acquisition Scenario

We apply our developed multi-stage portfolio framework for the case of a Naval Acquisition Scenario. The Naval Acquisition Scenario is based on the Littoral Combat Ship (LCS 2011) system model developed by Lockheed Martin and General Dynamics. The design of these ships allows for modular packages to be swapped for execution of a range of mission scenarios that include: Mine Counter Measure (MCM), Anti-Submarine Warfare (ASW) and Surface Warfare (SUW). Our simplified model consists of a hypothetical list of systems, listed in Table 1, that are available to the Navy for acquisition, and are presented with a corresponding Technology Readiness Levels (TRL). Although the number presented in the table are fictitious, the salient features of capability, requirements, cost and such, are represented. The (ASW, MCM, SUW, Unconventional Warfare) categories are the core mission packages, "Communications" represents the support communications systems available for deployment. Power represents the power generation systems available for deployment and in support of other systems.

The first six columns show capabilities of each system, and their respective numerical valuations. Column 7 and 8 are the *Power* and *Communications* requirement needed for operation of the listed systems, in providing the respective capabilities in Columns 1–6. Column 9 is the acquisition cost of the relevant system, assuming a TRL level of 8 or above; for systems less than this, the number is subject to uncertainty. Column 10 is the cost of research at each time period to promote a particular system's technology towards a TRL level 8—this can be thought of as a development cost.

We apply the recursive framework of the forward dynamic programming problem as represented in Equations 9–16 to our Naval Acquisition Scenario where the need is to evolve and acquire systems towards maximizing warfighter capabilities. The solution of the optimization at each decision epoch, assumes a value of “belief” in the future states, as dictated by the discount term Υ that takes a value between 0 and 1 and is assumed to be set by the practitioner. The result of the optimization problem, at each decision epoch, generates a list of systems acquired at the time step ($x_{q,t}^{TRL>8}$) which are then also included as existing systems in the subsequent epoch. Solution of the optimization problem also generates a list of systems to be researched as denoted by variable ($x_{q,t}^{R}$), that are then subject to a simulated dynamics of TRL evolution due to research investment; the evolution also generates a new cost of acquisition estimate for the researched systems as well.

Table 1. Naval Scenario Candidate System Specifications, Cost and Readiness Level

System Module	Weapon Package	Weapon Strike Range (miles)	Surface Detection Range (miles)	Anti Mine Detection Range (miles)	Unconv Warfare Payload (kg)	Comm. Capacity (Mbps)	Power Capacity (kW)	Power Req. (kW)	Comm. Bandwidth Req. (Mbps)	Cost of Acquisition (USD)	Cost of Research (USD)	TRL
ASW	Variable Depth	0	30	0	0	0	0	50	75	80000	20000	8
	Multi Fcn Tow	0	40	0	0	0	0	100	125	90000	22500	6
	Lightweight tow	0	50	0	0	0	0	150	150	100000	25000	6
	ASW Prototype 1	0	60	0	0	0	0	175	150	120000	30000	7
	ASW Prototype 2	0	70	0	0	0	0	180	100	130000	32500	7
MCM	RAMCS II	0	0	30	0	0	0	100	75	80000	20000	8
	ALMDS (MH-60)	0	0	40	0	0	0	150	125	90000	22500	7
	MCM Prototype 1	0	0	50	0	0	0	200	150	100000	25000	7
	MCM Prototype 2	0	0	60	0	0	0	250	175	120000	30000	7
	MCM Prototype 3	0	0	70	0	0	0	270	185	140000	35000	7
SUW	N-LOS Missiles	3	0	0	0	0	0	150	100	80000	20000	8
	Griffin Missiles	25	0	0	0	0	0	200	200	90000	22500	7
	SUW Prototype 1	50	0	0	0	0	0	250	300	100000	25000	7
	SUW Prototype 2	60	0	0	0	0	0	200	120	120000	30000	6
	SUW Prototype 3	70	0	0	0	0	0	200	300	130000	32500	6
Unconventional Warfare	Package System 1	0	0	0	100	0	0	25	50	70000	17500	8
	Package System 2	0	0	0	150	0	0	50	150	80000	20000	8
	Package System 3	0	0	0	200	0	0	75	200	90000	22500	8
Comm. Package	Package System 1	0	0	0	0	300	0	50	0	80000	20000	8
	Package System 2	0	0	0	0	400	0	75	0	90000	22500	8
	Package System 3	0	0	0	0	450	0	100	0	100000	25000	6
	Package System 4	0	0	0	0	500	0	150	0	100000	25000	6
	Package System 5	0	0	0	0	550	0	200	0	110000	27500	6
Power Package	Package System 1	0	0	0	0	0	350	0	0	80000	20000	8
	Package System 2	0	0	0	0	0	450	0	0	90000	22500	8
	Package System 3	0	0	0	0	0	550	0	0	100000	25000	7
	Package System 4	0	0	0	0	0	650	0	0	110000	27500	7
	Package System 5	0	0	0	0	0	750	0	0	120000	30000	6

Results

The forward optimization scheme of Equations 9–16 is solved over six decision epochs, and using a choice of two levels of belief (how much to favour TRL>8 systems in each epoch over research investment) are captured in Table 2 and Table 3. Table 2 lists, for each degree of belief (Υ = 1, 0.1), the acquisition of systems of TRL>8 at each decision epoch. A belief level of Υ =1 refers to a high preference policy on potentially investing in systems of higher value that may need research funding (TRL investment). A belief value of Υ = 0.1 refers to the converse where the policy is to invest in assets that are more readily available at the immediate decision epoch. It is assumes that for each value of Υ used, we assume a constant value throughout the decision epochs. In realistic settings however, the values of Υ can be adapted at each decision epoch; this process can either be through the practitioner’s insights or based on algorithmic rigor. Table 3 captures the research decisions (investment in system to potentially upgrade TRL) towards subsequent acquisition of the relevant system.

The results of Table 2 are intuitive; using a high preference value of Υ = 1.0, we can observe that the recursive optimization scheme does not invest in immediate systems at the early stages, but rather in the best valued TRL systems that can potentially improve the overall portfolio index at later stages. The “exploration” element of researching lower TRL technologies with potentially higher payoffs is seen in the decision to research such systems in Table 3. For example, at Υ = 1.0, the decision to acquire an ASW system is left to the latter stage at the second decision epoch, after ASW Prototype 2 has been researched and reached a TRL of 8 for subsequent acquisition. At the lower level of preference, Υ = 0.1, we observe that the policy favours the immediate acquisition of TRL>8 systems for short term gains.

An acquisitions practitioner could conceivably use sequential results to select an appropriate policy of Υ, based on practitioner insights into the acquisition environment. Additionally, the optimization framework addresses the combinatorial aspects of the systems interconnectivities, accounts of acquisition sequencing and maximizes the potential utility of yet-to-be introduced systems by evaluating potential value to the overall architecture, based on investment research progress towards TRL 8 status.

Table 2. Decision Epochs Acquisitions ($x_{q,t}^{TRL>8}$)

		Decision Epochs (Acquisitions)											
	Gamma Value	**1**	**0.1**	**1**	**0.1**	**1**	**0.1**	**1**	**0.1**	**1**	**0.1**	**1**	**0.1**
	System												
ASW	**Variable Depth**	**0**	**1**	0	1	**0**	**1**	0	1	**0**	**1**	0	1
	Multi Fcn Tow	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	Lightweight tow	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	ASW Prototype 1	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	ASW Prototype 2	**0**	**0**	1	0	**1**	**0**	1	0	**1**	**0**	1	0
MCM	**RAMCS II**	**0**	**1**	0	1	**0**	**1**	0	1	**0**	**1**	0	1
	ALMDS (MH-60)	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	MCM Prototype 1	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	MCM Prototype 2	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	MCM Prototype 3	**0**	**0**	1	0	**1**	**0**	1	0	**1**	**0**	1	0
SUW	**N-LOS Missiles**	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	Griffin Missiles	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	SUW Prototype 1	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	SUW Prototype 2	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	SUW Prototype 3	**0**	**0**	0	0	**0**	**0**	0	1	**1**	**1**	1	1
nconventior Warfare	**Package System 1**	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	Package System 2	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	Package System 3	**1**	**1**	1	1	**1**	**1**	1	1	**1**	**1**	1	1
Comm. Package	**Package System 1**	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**1**	0	1
	Package System 2	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	Package System 3	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	Package System 4	**0**	**0**	0	0	**1**	**0**	1	0	**1**	**0**	1	0
	Package System 5	**0**	**0**	0	0	**1**	**0**	1	0	**1**	**0**	1	0
Power Package	**Package System 1**	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	1
	Package System 2	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**1**	0	1
	Package System 3	**0**	**0**	0	0	**0**	**0**	0	0	**0**	**0**	0	0
	Package System 4	**0**	**0**	0	0	**1**	**0**	1	0	**1**	**0**	0	0
	Package System 5	**0**	**0**	0	0	**0**	**1**	0	0	**0**	**0**	1	0

Table 3. Decision Epochs Research ($x_{q,t}^{R}$)

	Decision Epochs (Research TRL)											
Gamma Value	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1
System												
Variable Depth	0	0	0	0	0	0	0	0	0	0	0	0
Multi Fcn Tow	0	0	0	0	0	0	0	0	0	0	0	0
Lightweight tow	0	0	0	0	0	0	0	0	0	0	0	0
ASW Prototype 1	0	0	0	0	0	0	0	0	0	0	0	0
ASW Prototype 2	1	0	0	0	0	0	0	0	0	0	0	0
RAMCS II	0	0	0	0	0	0	0	0	0	0	0	0
ALMDS (MH-60)	0	0	0	0	0	0	0	0	0	0	0	0
MCM Prototype 1	0	0	0	0	0	0	0	0	0	0	0	0
MCM Prototype 2	0	0	0	0	0	0	0	0	0	0	0	0
MCM Prototype 3	1	0	0	0	0	0	0	0	0	0	0	0
N-LOS Missiles	0	0	0	0	0	0	0	0	0	0	0	0
Griffin Missiles	0	0	0	0	0	0	0	0	0	0	0	0
SUW Prototype 1	0	0	0	0	0	0	0	0	0	0	0	0
SUW Prototype 2	0	0	0	0	0	0	0	0	0	0	0	0
SUW Prototype 3	1	1	1	1	1	1	1	0	0	0	0	0
Package System 1	0	0	0	0	0	0	0	0	0	0	0	0
Package System 2	0	0	0	0	0	0	0	0	0	0	0	0
Package System 3	0	0	0	0	0	0	0	0	0	0	0	0
Package System 1	0	0	0	0	0	0	0	1	0	0	0	0
Package System 2	0	0	0	0	0	0	0	1	0	1	0	1
Package System 3	0	1	0	0	0	0	0	0	0	0	0	0
Package System 4	1	1	1	1	0	1	0	0	0	0	0	0
Package System 5	1	0	1	1	0	1	0	0	0	0	0	0
Package System 1	0	0	0	0	0	0	0	1	0	1	0	0
Package System 2	0	0	0	0	0	0	0	1	0	0	1	0
Package System 3	1	0	1	1	0	1	0	0	0	0	0	0
Package System 4	1	1	1	0	0	0	0	0	0	0	0	0
Package System 5	0	1	0	1	1	0	1	0	1	0	0	0

Conclusions and Summary

The management of acquisitions of highly interdependent systems, is a difficult endeavor due to complex combinatorial interdependencies and uncertainties between current and yet-to-be introduced systems. Research in this paper complements prior work in robust portfolio approaches to managing defense acquisitions, by providing a framework towards managing dynamically evolving acquisitions decisions in environments with dynamically constrained costs and schedules. The framework is based on multi-period dynamic programming techniques, is intuitive in nature, and it has shown promise in assisting practitioners in evolving acquisitions. The framework can account for sequential research of new, yet-to-be introduced systems, and evaluate acquisitions of existing systems within a dynamic and quantitatively objective framework. Future work can potentially expand the current dynamic framework by introducing algorithmic innovations in statistically evaluating the correlated properties of potential investments of value (say correlation in research funded tasks), as a means of improving the forward programming efficiency of the multi-period portfolio framework.

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