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Ship Maintenance Processes with Collaborative Product Lifecycle Management and 3D Terrestrial Laser Scanning Tools: Reducing Costs and Increasing Productivity

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Preface & Acknowledgements

During his internship with the Graduate School of Business & Public Policy in June 2010, U.S. Air Force Academy Cadet Chase Lane surveyed the activities of the Naval Postgraduate School's Acquisition Research Program in its first seven years. The sheer volume of research products—almost 600 published papers (e.g., technical reports, journal articles, theses)—indicates the extent to which the depth and breadth of acquisition research has increased during these years. Over 300 authors contributed to these works, which means that the pool of those who have had significant intellectual engagement with acquisition issues has increased substantially. The broad range of research topics includes acquisition reform, defense industry, fielding, contracting, interoperability, organizational behavior, risk management, cost estimating, and many others. Approaches range from conceptual and exploratory studies to develop propositions about various aspects of acquisition, to applied and statistical analyses to test specific hypotheses. Methodologies include case studies, modeling, surveys, and experiments. On the whole, such findings make us both grateful for the ARP's progress to date, and hopeful that this progress in research will lead to substantive improvements in the DoD's acquisition outcomes.

As pragmatists, we of course recognize that such change can only occur to the extent that the potential knowledge wrapped up in these products is put to use and tested to determine its value. We take seriously the pernicious effects of the so-called "theory–practice" gap, which would separate the acquisition scholar from the acquisition practitioner, and relegate the scholar's work to mere academic "shelfware." Some design features of our program that we believe help avoid these effects include the following: connecting researchers with practitioners on specific projects; requiring researchers to brief sponsors on project findings as a condition of funding award; "pushing" potentially high-impact research reports (e.g., via overnight shipping) to selected practitioners and policy-makers; and most notably, sponsoring this symposium, which we craft intentionally as an opportunity for fruitful, lasting connections between scholars and practitioners.

A former Defense Acquisition Executive, responding to a comment that academic research was not generally useful in acquisition practice, opined, "That's not their [the academics'] problem—it's ours [the practitioners']. They can only perform research; it's up to us to use it." While we certainly agree with this sentiment, we also recognize that any research, however theoretical, must point to some termination in action; academics have a responsibility to make their work intelligible to practitioners. Thus we continue to seek projects that both comport with solid standards of scholarship, and address relevant acquisition issues. These years of experience have shown us the difficulty in attempting to balance these two objectives, but we are convinced that the attempt is absolutely essential if any real improvement is to be realized.

We gratefully acknowledge the ongoing support and leadership of our sponsors, whose foresight and vision have assured the continuing success of the Acquisition Research Program:

- Office of the Under Secretary of Defense (Acquisition, Technology & Logistics)
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- Office of Procurement and Assistance Management Headquarters, Department of Energy

We also thank the Naval Postgraduate School Foundation and acknowledge its generous contributions in support of this Symposium.

James B. Greene, Jr.
Rear Admiral, U.S. Navy (Ret.)

Keith F. Snider, PhD
Associate Professor

Panel 9 – New Dimensions in Acquisition Management

Wednesday, May 11, 2011	
1:45 p.m. – 3:15 p.m.	**Chair: Joseph L. Yakovac Jr.,** LTG, USA, (Ret.), NPS; former Military Deputy to the Assistant Secretary of the Army (Acquisition, Logistics, & Technology) ***Ship Maintenance Processes with Collaborative Product Lifecycle Management and 3D Terrestrial Laser Scanning Tools: Reducing Costs and Increasing Productivity*** David Ford, Texas A&M, Thomas Housel and Johnathan Mun, NPS ***Analysis of Alternatives in System Capability Satisficing for Effective Acquisition*** Brian Sauser, Jose Ramirez-Marquez, and Weiping Tan, Stevens Institute of Technology ***Proposed Methodology for Performance Prediction and Monitoring for an Acknowledged Systems of Systems*** Carly Jackson and Rich Volkert, SSC Pacific

Joseph L. Yakovac Jr.—Lt. Gen. Yakovac retired from the United States Army in 2007, concluding 30 years of military service. His last assignment was as director of the Army Acquisition Corps and Military Deputy to the Assistant Secretary of Defense for Acquisition, Logistics, and Technology. In those roles, Lt. Gen. Yakovac managed a dedicated team of military and civilian acquisition experts to make sure America's soldiers received state-of-the-art critical systems and support across a full spectrum of Army operations. He also provided critical military insight to the Department of Defense senior civilian leadership on acquisition management, technological infrastructure development, and systems management.

Previously, Lt. Gen. Yakovac worked in systems acquisition, U.S. Army Tank-Automotive Command (TACOM), and in systems management and horizontal technology integration for the Office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology. He has also served as executive officer and branch chief for the Bradley Fighting Vehicle and as a brigade operations officer and battalion executive officer, U.S. Army Europe and U.S. Army Tank-Automotive Command (TACOM).

Lt. Gen. Yakovac was commissioned in the infantry upon his graduation from the U.S. Military Academy at West Point. He served as a platoon leader, executive officer, and company commander in mechanized infantry units. He earned a Master of Science in Mechanical Engineering from the University of Colorado at Boulder before returning to West Point as an assistant professor.

Lt. Gen. Yakovac is a graduate of the Armor Officer Advanced Course, the Army Command and General Staff College, the Defense Systems Management College, and the Industrial College of the Armed Forces. He has earned the Expert Infantry Badge, the Ranger Tab, the Parachutist Badge, and for his service has received the Distinguished Service Medal, the Legion of Merit three times and the Army Meritorious Service Medal seven times.

Ship Maintenance Processes with Collaborative Product Lifecycle Management and 3D Terrestrial Laser Scanning Tools: Reducing Costs and Increasing Productivity

David Ford—Associate Professor of Construction Engineering and Management, Zachry Department of Civil Engineering, Texas A&M, and Research Associate Professor of Acquisition, Graduate School of Business and Public Policy, NPS. Dr. Ford has also held a faculty position at the University of Bergen, Norway. He received his doctorate from MIT in Dynamic Engineering Systems. His current research interests include the sustainability of engineered systems, the use of real options for risk management and policy implementation, tipping point dynamics, project management and control, and the management of professional services firms. Dr. Ford's research work has been published in several academic journals, including *IEEE Transactions on Engineering Management*, *European Journal of Operations Research*, *System Dynamics Review*, *Construction Management and Economics*, *ASCE Journal of Construction Engineering and Management*, *ASCE Journal of Management in Engineering*, *and Engineering Construction and Architectural Management.* He currently serves as a Managing Editor of the *System Dynamics Review*. [DavidFord@tamu.edu]

Thomas Housel—Professor, Information Sciences, Naval Postgraduate School. Professor Housel specializes in valuing intellectual capital, knowledge management, telecommunications, information technology, value-based business process re-engineering, and knowledge value measurement in profit and non-profit organizations. His current research focuses on the use of knowledge-value added (KVA) and real options models in identifying, valuing, maintaining, and exercising options in military decision-making. His work on measuring the value of intellectual capital has been featured in a *Fortune* cover story (October 3, 1994) and *Investor's Business Daily*, numerous books, professional periodicals, and academic journals (most recently in the *Journal of Intellectual Capital*, 2005). [tjhousel@nps.edu]

Johnathan Mun—Professor of Research, Information Sciences Department, NPS. Professor Mun is the founder and CEO of Real Options Valuation, Inc., a consulting, training and software development firm specializing in real options, employee stock options, financial valuation, simulation, forecasting, optimization, and risk analysis located in northern California. He is the creator of the *Super Lattice Solver* software, *Risk Simulator* software, and *Employee Stock Options Valuation* software at the firm. He has also authored numerous books, including *Real Options Analysis: Tools and Techniques*, *Real Options Analysis Course: Business Cases*, *Applied Risk Analysis: Moving Beyond Uncertainty*, and others. [jcmun@nps.edu]

Abstract

The current cost-constrained environment within the federal government and the Department of Defense (DoD) requires a defensible approach to cost reductions without compromising the productivity of core defense processes. Therefore, defense leaders today must maintain and modernize the United States Armed Forces to retain technological superiority while simultaneously balancing defense budget cost constraints and extensive military operational commitments. At the same time, defense leaders must also navigate a complex information technology (IT) acquisition process. The DoD spends over $63 billion annually, or 14% of its total budget, on defense maintenance programs throughout the world (Office of the Deputy Under Secretary of Defense [Logistics and Material Readiness], 2006).

One such core process that is central to naval operations, is the ship maintenance process. This process alone accounts for billions of the overall Navy annual budget. There have been a series of initiatives designed to reduce the cost of this core process, including ship maintenance (SHIPMAIN), which was designed to standardize ship maintenance alterations in order to take advantage of the cost-savings learning curve.

The main problem in SHIPMAIN has been that the normal cost-reduction learning curve for common ship maintenance items across a series of ship platforms has not yet been realized. The purpose of SHIPMAIN was to take advantage of this cost-savings learning curve over time.

This study suggests that unless the SHIPMAIN process employs 3D Terrestrial Laser Scanning (3D TLS) and collaborative Product Lifecycle Management (collab-PLM) tools, SHIPMAIN will be unlikely to obtain the learning curve benefits. This study uses the knowledge value added (KVA) + systems dynamics (SD) + integrated risk management (IRM) methodology to estimate, analyze, and optimize the potential cost savings and productivity improvements within the context of an optimal portfolio.

Introduction

The current cost-constrained environment within the federal government and the Department of Defense (DoD) requires a defensible approach to cost reductions without compromising the productivity of core defense processes. Therefore, defense leaders today must maintain and modernize the United States Armed Forces to retain technological superiority while simultaneously balancing defense budget cost constraints and extensive military operational commitments. At the same time, defense leaders must also navigate a complex information technology (IT) acquisition process. The DoD spends over $63 billion annually, or 14% of its total budget, on defense maintenance programs throughout the world (Office of the Deputy Under Secretary of Defense [Logistics and Material Readiness], 2006).

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The main problem in SHIPMAIN has been that the normal cost-reduction learning curve for common ship maintenance items across a series of ship platforms has not yet been realized. Figure 1 provides a notional picture of this phenomenon. The purpose of SHIPMAIN was to take advantage of this cost-savings learning curve over time.

This study suggests that unless the SHIPMAIN process employs 3D Terrestrial Laser Scanning (3D TLS) and collaborative Product Lifecycle Management (collab-PLM) tools, SHIPMAIN will be unlikely to obtain the learning curve benefits. This study uses the knowledge value added (KVA) + systems dynamics (SD) + integrated risk management (IRM) methodology to estimate, analyze, and optimize the potential cost savings and productivity improvements within the context of an optimal portfolio. As demonstrated in the first phase of this study using KVA+SD+IRM, the potential cost savings for ship maintenance processes is substantial when SHIPMAIN incorporates collab-PLM and 3D TLS tools. The use of these tools will allow the SHIPMAIN process to take advantage of the normal production cost-savings learning curve.

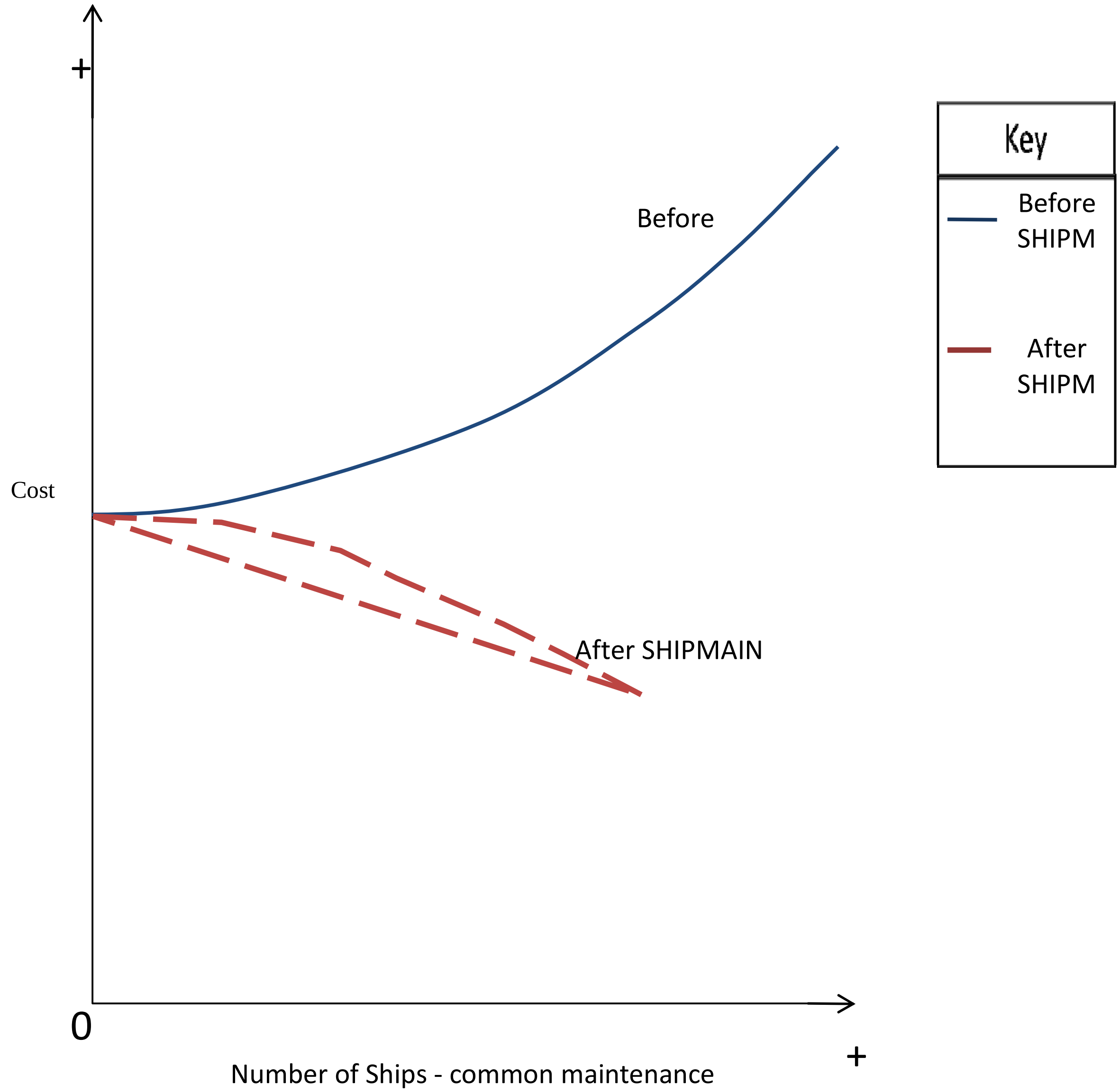

Figure 1. Learning Curve Before and After SHIPMAIN

The inverse learning curve ("Before SHIPMAIN") results in cost increases, rather than the expected cost decreases found in the learning curve phenomena in all other industries (with the possible exception of certain software firms' products).

SHIPMAIN was created, in part, to address this glaring disparity in ship maintenance performance within the Navy. However, the initial instantiation of SHIPMAIN did not include two recommended technologies: that is, 3D TLS + collab-PLM, which were deemed necessary by Bob Stout, the creator of SHIPMAIN, for ensuring the success of the new standardized approach (i.e., normal learning curve cost savings).

These technologies, if currently employed in ship building and continually used in the maintenance cycle, should lead to the benefits projected in this study. The use of the tools in ship building will allow for the reuse of their outputs (i.e., 3D images of the entire ship inside and out can be distributed and manipulated remotely by a wide variety of vendors) in the ship maintenance core process. Using the tools across the entire ship building and maintenance lifecycle should result in substantial cost savings.

To evaluate and select ship maintenance options (e.g., use of the collab-PLM + 3D TLS technologies) that promise the best cost savings and highest returns, measurement methods are essential to define, capture, and measure the cost savings and returns on these technologies. In addition to estimating potential cost savings, these measurement methods also must incorporate and analytically quantify elements of uncertainty and risks inherent in predicting the future value of these technologies. This will allow acquisition professionals to develop ways to mitigate these risks through strategic options, and analytically develop and allocate budgets to optimize project portfolios.

The Naval Postgraduate School (NPS) developed the Knowledge Value Added + Systems Dynamics + Integrated Risk Management (KVA+SD+IRM) valuation framework to address these issues. KVA+SD+IRM analysis is designed to support technology portfolio acquisitions and to empower decision-makers by providing performance-based data and SD scenario analysis. With historical data provided by KVA, potential strategic investments can then be evaluated with IRM analysis.

In this study, the KVA+SD+IRM framework is used to quantify process cost savings and the potential benefits of selecting collab-PLM+3D TLS technology in the ship SHIPMAIN program. SHIPMAIN is a large program with many interrelated concepts, instructions, policies, and areas of study. Although the quantitative scope of the research was constrained to Phases IV and V of the SHIPMAIN process, the technologies evaluated in this research are likely to provide additional benefits (e.g., more accurate cost-estimation, higher quality, less rework and more efficient system dynamics) across all phases of SHIPMAIN.

The first section of this paper explicates the KVA+SD+IRM framework. In section two, a description of the SHIPMAIN program is provided. The third section describes the collab-PLM+3D TLS technologies. Following this, the KVA+SD+IRM framework is applied to Phase IV of SHIPMAIN under two scenarios: current “As-Is” and potential “To-Be” (i.e., SHIPMAIN supported by collab-PLM + 3D TLS). Results of the KVA and SD scenario analysis are presented with the implications for the next phase of the research where IRM will be used to forecast an optimized portfolio controlling for risk.

KVA +SD+ IRM Framework

The KVA+SD+IRM framework measures operating performance, cost-effectiveness, return on investment, risk quantification, strategic real options (capturing strategic flexibility), and analytical portfolio optimization. The use of SD scenario modeling provides a means to estimate the impact of SHIPMAIN process improvements with collab-PLM + 3D TLS technologies over time. The analysis can be compared with historical static data to assess the fidelity of the SD models.

The SD scenario results provide distributions around model parameters so that the IRM analysis can be based on distributions of parameter estimates instead of single-point estimates. The framework then can provide more realistic portfolio optimization to evaluate the technologies in terms of risks while taking into account uncertainty in estimating future benefits. The benefits of this framework include the following:

- provides high fidelity models of potential cost savings and value of specific processes, functions, departments, divisions, or organizations in common units;

- provides scenario models based on historical data in terms of costs and benefits of specific processes and tasks for programs or organizations;
- helps meet regulatory compliance guidelines (such as the Clinger-Cohen Act of 1996) mandating portfolio management for federal agencies;
- highlights current operational cost inefficiencies, as well as potential cost avoidance; and
- improves current and potential portfolio investments by estimating potential total value created.

KVA+SD provides the data sets for estimating potential cost savings based on the target technologies that can be used in estimating the strategic flexibility options value of these technologies, as well as providing the data required for a rigorous quantitative portfolio optimization analysis. Management can drill down to understand the cost of each process from a common reference point as well as the potential cost-savings contributions to the bottom line using the KVA+SD+IRM framework. The Navy acquisitions community can use the framework to enhance existing cost analysis tools, as well as to value specific operations, such as ship maintenance or ship building.

SHIPMAIN

In August 2006, the *Surface Ship and Carrier Entitled Process for Modernization (SSCEPM) Management and Operations Manual* became the Navy's official document for the modernization of all Surface Ships and Aircraft Carriers (Commander, Naval Sea Systems Command, 2006). SSCEPM provides the policy and processes associated with SHIPMAIN for planning, budgeting, engineering, and installing timely effective and affordable shipboard improvements while maintaining configuration management and supportability. The SHIPMAIN process represents a sweeping change in the modernization of Surface Ships and Carriers. The SHIPMAIN process streamlines and consolidates a number of existing modernization practices, processes, meetings, and supporting documents to provide a single, hierarchical decision-making process for modernizing Surface Ships and Carriers.

The SHIPMAIN process comprises five distinct phases[1] and three Decision Points (DP)[2] that take a proposed change from concept to completion in a single Ship Change Document (SCD). The SCD is a single lifecycle-management document depicting a modernization change from concept to completion for ships (Commander, Naval Sea Systems Command, 2006, § 3, p. 3-2). Although SHIPMAIN has a functional governance structure and supporting business rules, it has yet to reach a fully implemented state, especially in Phases IV and V. Business rules for Phases IV and V are in a maturing phase, and the process owners are regularly gathering input from stakeholders to resolve issues and refine the business rules in order to move forward with this initiative.

SHIPMAIN is designed to take advantage of best business practices from industry that lead to cost reductions based on the production learning curve. The Navy implemented the SHIPMAIN process in FY 2004 to do the following:

- increase efficiency of maintenance and modernization process without compromising effectiveness;

[1] Five Phases: I-Conceptual, II-Preliminary Design, III-Detailed Design, IV-Implementation, V-Installation (Commander, Naval Sea Systems Command, 2006).
[2] DPs occur at the conclusion of Phases I-III. Each DP is an approval for funding of successive phases and has an associated Cost Benefit Analysis (CBA), Alteration Figure of Merit (AFOM), and Recommended Change Package (RCP; Commander, Naval Sea Systems Command, 2006).

- define common planning process for surface ship maintenance and alterations;
- install a disciplined management process with objective measurements; and
- institutionalize that process and provide continuous improvement methodology (Commander, Naval Sea Systems Command, 2006).

SHIPMAIN seeks to identify and eliminate redundancies in maintenance processes. It provides a single entitled process, assisting the Navy in realizing the maximum cost savings in maintenance by eliminating time lags, prioritizing ship jobs, and empowering Sailors in their maintenance decisions (Commander, Naval Sea Systems Command, 2006). The five-phase process was originally designed to employ collab-PLM + 3D TLS. However, these technologies were not incorporated in the implementation of the SHIPMAIN program. This study examines the potential cost savings and productivity improvements that would feed an IRM portfolio optimization analysis when these two technologies are used to support the SHIPMAIN processes. The SD models compare the SHIPMAIN's Phase Four process with and without the supporting technology to determine the potential long-term cost savings.

3D Terrestrial Laser Scanning Technology

Terrestrial Laser Scanning technology is currently used in a variety of industries. According to industry analysts, laser scanner manufacturers and related software and service providers report strong activity across many markets, including the following: shipbuilding, offshore construction and repair, onshore oil and gas, fossil and nuclear power, civil and transportation infrastructure, building, automotive and construction equipment, manufacturing, and forensics (Greaves & Jenkins, 2007, para. 1). Sales of 3D Terrestrial Laser Scanning hardware, software, and services reached $253 million in 2006—a growth of 43% over 2005 (Greaves & Jenkins, 2007).

Most manufacturers' scanners work by scanning a target space with a laser light mounted on a highly articulating mount, enabling data capture in virtually any orientation with minimal operator input. Some also incorporate a digital camera that simultaneously captures a 360° field-of-view color photo image of the target. Once the capture phase is complete, the system automatically executes proprietary point-processing algorithms to process the captured image. The system can generate an accurate[3] digital 3D model of the target space, automatically fuse image texture onto 3D model geometry, export file formats ready for commercial, high-end design, and import them into 2D/3D Computer-aided Design (CAD) packages.

Collaborative Product Lifecycle Management Technology

Collab-PLM technology provides a common platform to electronically integrate 3D TLS images in three dimensional surface representations to enable collaboration among all parties involved in a given project regardless of their geographic location. It also provides a means to store the images and all related maintenance work within a common database accessible by all participants in a ship alteration or modernization project.

PLM is defined by CIMdata as a strategic business approach applying a consistent set of business solutions in support of the collaborative creation, management,

[3] NSRP's study (2006 & 2007b) requirement was within 3/16 of an inch to actual measurements.

dissemination, and use of product definition information across the extended enterprise, from concept to end of life.[4] It integrates people, processes, and information.

The collab-PLM tools include technologies that support data exchange, portfolio management, digital manufacturing, enterprise application integration, and workflow automation. A range of industries have invested in collab-PLM solutions, including those involved in aerospace and defense, automotive and transportation, utilities, process manufacturing, and high-tech development and manufacturing. The collab-PLM market is poised for further growth with vendors expanding product offerings as the industry evolves. Figure 2 indicates the evolution of PLM applications, illustrating their stages before reaching the "plateau of productivity" in the mainstream market.

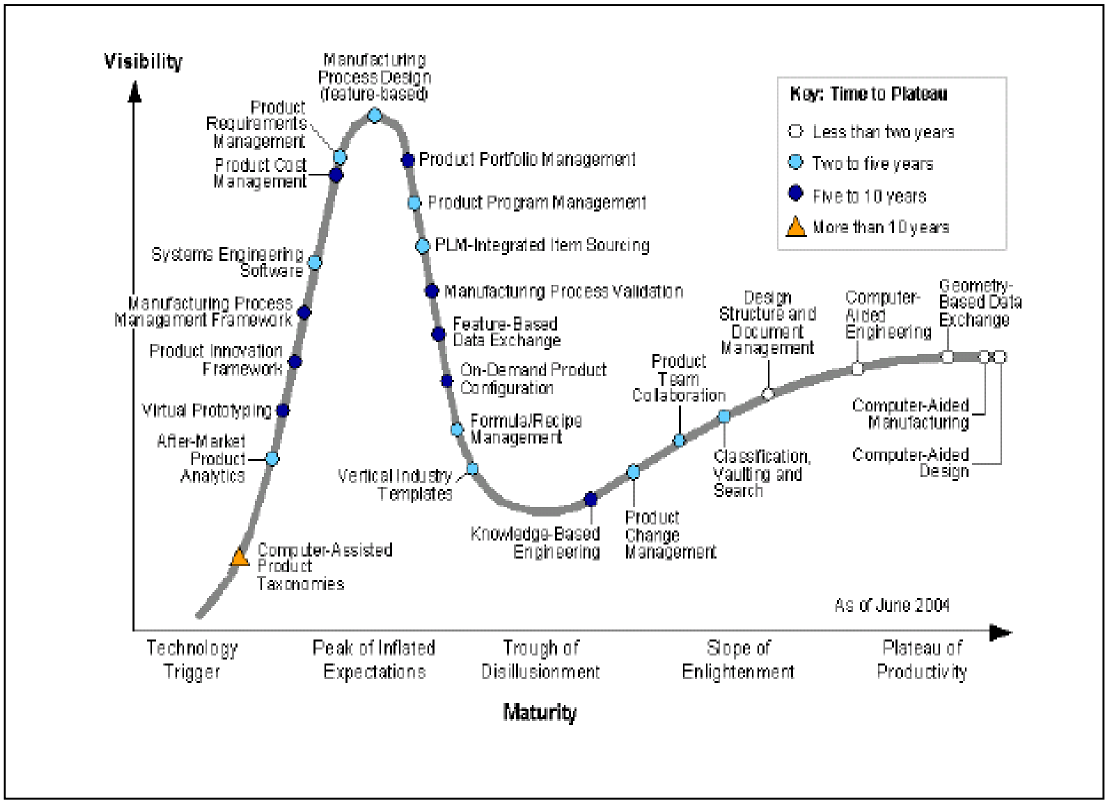

Figure 2. Evolution of PLM

(Halpern & Smith, 2004)The assimilation of 3D Terrestrial Laser Scanning and Product Lifecycle Management technologies into Phases IV and V of SHIPMAIN could be the key to the Navy's goal of reducing costs while still maintaining a superior level of effectiveness. The KVA+SD+IRM valuation framework can be applied to quantify the potential impact of these technologies on the SHIPMAIN directive by comparing "As-Is" and "To-Be" scenarios.

[4] CIMdata is a consulting firm with over 20 years of experience in strategic IT applications and is an acknowledged leader in the application of PLM and related technologies (CIMdata, 2007a).

SHIPMAIN: With and Without Collab-PLM+3D TLS Technologies

The KVA+SD+IRM valuation framework will be used to demonstrate how the integration of these two technologies within Phase IV of SHIPMAIN could result in substantial cost savings and decreased fleet cycle time via significant productivity improvements.

A prior study of the ship maintenance process (Komoroski, 2005) identified seven sequential processes utilized to plan for ship maintenance alterations on U.S. Navy surface ships, shown in Figure 3. An “As-Is” environment without collab-PLM+3D TLS technologies was modeled to develop the baseline cost and productivity data using the KVA method.[5]

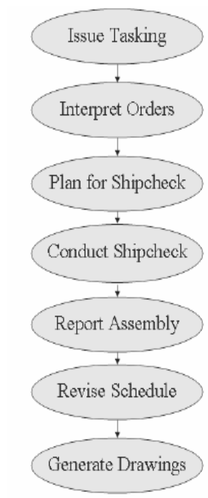

Figure 3. Planning Yard Core Processes
(Komoroski, 2005, p. 36)

The baseline costs for these Phase IV processes was estimated to be $45 million per year[6] to execute the shipyard planning process cycle 40 times across the four public shipyards. Adding 3D laser scanning to the planning process cycle lowered expenses a projected 84% (to less than $8 million), as seen in Table 1. Introduction of 3D laser scanning in the “To-Be” environment could result in projected cost savings of nearly $37 million because Subprocesses 3, 4, and 7 were re-engineered (Komoroski, Housel, Hom, & Mun, 2006).

The second notional environment “To-Be” evaluated the effects of adding 3D laser scanning and the collaborative PLM suite of software to the “As-Is” baseline. Projections for this scenario (based from increased savings in Subprocesses 3, 4, and 7, as well as additional savings realized in Subprocesses 2 and 5) included a cost savings of 90% or approximately $40 million.

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[5] Baseline data for As-Is environment was compiled by conducting extensive interviews with SMEs of the Puget Sound Planning Yard.

[6] The baseline costs were based on the execution of the shipyard planning process cycle 40 times across the four public shipyards per year.

Table 1. KVA Results—Analysis of Costs
(Komoroski et al., 2006, p. 36)

	Process Title	"AS-IS"
1	ISSUE TASKING	$173,500
2	INTERPRET ORDERS	$520,000
3	PLAN FOR SHIP CHECK	$1,655,000
4	CONDUCT SHIP CHECK	$2,604,500
5	REPORT ASSEMBLY	$235,000
6	REVISE SCHEDULE	$131,000
7	GENERATE DRAWINGS	$39,386,000
	TOTALS	**$44,705,000**

KVA Results

The cost analysis results were based on the "As-Is" KVA baseline analysis. The return on investment (ROI) analysis is presented in Table 2.

Table 2. KVA Results—Analysis on ROI

Core Process	Process Title	"AS-IS" ROI
1	Issue Tasking	-69%
2	Interpret Orders	518%
3	Plan for Ship Check	-99%
4	Conduct Ship Check	552%
5	Report Assembly	783%
6	Revise Schedule	1375%
7	Generate Drawings	-37%

This baseline model provided the inputs for the SD model. A comparison with the SD model and the static KVA analysis revealed that the SD model was of high fidelity and could be used to iterate parameters for further analysis of the "To-Be" scenarios using time periods and the effects of the two technologies. While these results might be considered relatively positive, the addition of collab-PLM+3D TLS technologies promise to return even more significant savings.

Systems Dynamics Model and Results

The SD model was initially used to improve estimates of cost savings through the implementation of collab-PLM+3D TLS technologies. The model structure reflects the set of serial core processes shown in Figure 3. Like the previous KVA analysis of SHIPMAIN, the SD model simulates the 28 subprocesses that can be clustered into those seven core processes. The impacts of the subprocesses were aggregated for the current cost-savings estimates. Analysis at the core process and subprocess level of aggregation will be part of the future work to be described later.

In the model, each subprocess can be constrained by either the resources provided (e.g., headcount of workforce applied to the subprocess) or the availability of work. Previous KVA modeling of SHIPMAIN assumed steady state conditions for one year. Under these conditions, work availability does not constrain progress. However, under the changing and uncertain conditions that better reflect actual circumstances, the availability of work can significantly impact performance. For example, if the number of ships entering the yard drops below some level, certain subprocesses could complete the work on all the ships in the yard that are available and will be left idle. Conditions such as these will be modeled with the SD model for the Integrated Risk Management portion of the research, as described later. Steady state conditions were assumed for the cost-saving investigation described here.

Several factors that impact SHIPMAIN benefits and costs that were not included in the previous work but can significantly impact cost savings were incorporated into the SD model. Model improvements that impacted benefits include the following:

- variation in the number of ships that are in the process of adopting of PLM+3D TLS in larger numbers of shipyards;
- increase in number of ships that can be processed through the yards if PLM+3D TLS are adopted due to the reduced cycle time of individual ships with PLM+3D TLS; and
- lifespan of the use of PLM+3D TLS in the shipyards before adoption of a new technology.

Model changes that improved the accuracy of cost estimates include the following:

- average costs of common units of output (CUO)7 in $/CUO were calculated;
- initial costs to purchase collaborative PLM software and license users were included; and
- costs to install 3D imaging equipment at the shipyards using 3D TLS were included.

Cost savings were calculated as follows:

$$\Pi = \upsilon\lambda$$

where,

Π = cost savings,

υ = volume of benefits generated, and

λ = unit cost savings.

In other words, the cost savings is equal to volume of benefits generated multiplied by the unit cost savings. Volume of benefits generated is the number of common units of output (CUO) produced under the adoption ("To-Be") scenario.

$$\lambda = \lambda_{wo} - \lambda_{w}$$

λ_{wo} = denotes SHIPMAIN unit cost without PLM+3D TLS ("As-Is") scenario, and
λ_{w} = denotes SHIPMAIN unit cost with PLM+3D TLS ("To-Be") scenario.

Unit cost$_{wo}$ = Process Cost$_{wo}$ / CUO generated$_{wo}$

Unit cost$_{w}$ = Process Cost$_{w}$ / CUO generated$_{w}$

For both the "with" (w subscript) and "without" (wo subscript) conditions:

Process Cost = Initial System Costs + Operations Costs, and

Initial System Costs = Software purchase and installation cost + (3D TLS installation per yard cost) * (Yards adopting PLM+3D TLS).

The software purchase and installation cost (estimated to be $1.6 million) was amortized evenly over the product life span. The cost of installing the 3D TLS in a yard (estimated to be $80,000 per yard) was amortized evenly over the first year of use.

Operations Costs = $\sum_{\text{Lifespan}}\sum_{\text{subprocesses}}$ (Subprocess Headcount * Daily salary * Subprocess duration * Shipcheck rate)

CUO generated = $\sum_{\text{subprocesses}}$ (Shipcheck subprocessing rate * (Operator Knowledge applied/shipcheck + IT Knowledge applied/shipcheck))

IT Knowledge applied/shipcheck = (Subprocess fraction performed by IT * Operator Knowledge applied/shipcheck)

Shipcheck subprocessing rate = Current subprocessing rate * Increase due to cycle time reduction

Current (i.e., without collaborative PLM + 3D TLS) subprocessing rates, headcounts, durations, and fractions performed by IT were developed based on information collected from subject-matter experts as part of the previous KVA research by Komoroski (2005). Estimates of the software purchase and installation cost and installation costs of the 3D TLS systems in shipyards was collected as part of the current research in spring 2011 from a vendor representative. The vendor representative also reported that other industries experience reductions in cycle time (in the current study this would be average ship processing duration) ranging from 20% to 60%. Increases in Current subprocessing rates were calculated from these values using Little's Law (Sterman, 2000), which states (using SHIPMAIN concepts) that, averaged across many processing durations, under steady state conditions:

Ships in yard = ship flow through the yard * average ship process duration.

For example, if the four Navy yards alter 40 ships/year and each ship requires an average of 3 months (=0.25 years) to alter, the four yards have a capacity to work on 10 ships at a time:

10 ships = 40 ships/year * 0.25 years

[7] Common units of output (CUO) are the measure of benefits developed in the Knowledge Value Analysis (KVA) methodology and reflect the amount of knowledge applied in each performance of a subprocess.

If the adoption of collaborative PLM and 3D TLS reduces the average ship processing duration by 20% to 2.4 months (=0.20 years) and the four yards retain the same capacity (10 ships),

10 ships = 50 ships/year * 0.20 years

This represents a 25% increase in processing, which is reflected in the model with an increase due to cycle time reduction equal to 1.25 (50 ships per year / 40 ships per year). Similarly, a 60% reduction in cycle time generates a 150% increase in processing and an increase due to cycle time reduction equal to 2.50.

10 ships = 100 ships/year * (3*0.40)/12)

100 ships per year/40 ships per year = 2.50

Model Testing

The model was tested with standard tests of model validation used to assess SD models (Sterman, 2000), including structural similarity to the actual system, unit consistency, realistic behavior under extreme conditions, and similarity of simulated performance with previous models (KVA analysis by Komoroski, 2005, in this case). Return on Knowledge (ROK) values for the 28 subprocesses as simulated are shown in Table 3. (ROK represents a basic productivity performance measure and is proportionate to ROI. The only difference is that ROK = Revenue/Cost and ROI = Revenue-Cost/Cost.)

The values in Table 3 match those generated by the previous KVA analysis for the same conditions (Komoroski, 2005), supporting the ability of the SD model to generate realistic performance measures. Based on these tests, the model was found to reflect the actual system adequately for use in investigating cost savings due to the adoption of collaborative PLM and 3D TLS by SHIPMAIN processes.

Table 3. Simulated SHIPMAIN Return on Knowledge for Subprocesses

Subprocess No.	Subprocess Description	Annual Benefits (CUO)	Annual Costs ($)	Return on Knowledge (ROK)
1a.	Plan SHIPCHECK budget allocations.	52.00	54,219.87	0.00
1b.	Coordinate and build schedule.	52.00	32,531.98	0.00
1c.	PLM oversee entire task.	35,880.00	86,751.96	0.41
2a.	Coordinate and communicate with follow codes and outside organizations.	720,000.56	56,550.11	12.73
2b.	Begins data collection pertaining to tasking.	1,380,000.00	135,550.38	10.18
2c.	Create Job Information Sheet (JIS) for each unique "job."	672,001.38	135,550.38	4.96
3a.	Form shipcheck team.	84.00	5,422.00	0.02
3b.	Get permission to go to ship.	200.00	2,711.00	0.07
3c.	Gather data applicable to shipcheck: review guidance, drawings, schematics	19,320.00	339,300.25	0.06
3d.	Physically gather tools required for SHIPCHECK.	40.00	27,144.04	0.00
4a.	Travel time. Transport team to ship.	40.00	135,719.91	0.00
4b.	Manage overall process.	52,900.00	54,219.87	0.98
4c.	Conduct in-brief and out-brief with ship's crew.	21,160.00	2,711.00	7.81
4d.	Liason with ship's crew, including conflict management and resolution.	1,379,999.88	43,375.98	31.81
4e.	Conduct ship walkthru: identify and resolve interferences between new installations	4,139,999.75	90,479.88	45.76
4f.	Determine alteration-pertinent capacities.	184,800.20	226,200.42	0.82
4g.	Collect "removal data" for equipment and material to be removed	35,999.99	90,479.88	0.40
4h.	Scan & capture point cloud images for applicable areas and compartments.	10,763,999.00	45,239.94	237.93
4i.	Photograph images for SHIPALTS with digital camera.	17,500.01	36,192.07	0.48
4j.	Create SHIPALT material lists.	1,655,999.88	180,959.77	9.15
4k.	Travel time. Transport team from ship.	40.00	135,719.91	0.00
5a.	Determine and list conflicts between subsystems.	1,379,999.88	113,100.21	12.20
5b.	Create SHIPALT Report.	3,239.99	9,048.02	0.36
6a.	Organize data to update DIS.	1,287,999.88	113,100.21	11.39
6b.	Develop drawing "list" or schedule.	144.00	9,048.02	0.02
6c.	Expected manhours determined.	144.00	9,048.02	0.02
7b.	Conduct data processing for captured point clouds	18,215,998.00	271,439.81	67.11
7c.	Model processed data to 3D.	28,979,998.00	2,035,794.75	14.24
7d.	Generate 2D drawings.	24,149,998.00	11,309.99	2,135.28

Collaborative PLM and 3D TLS Adoption Conditions and Simulation Results

SHIPMAIN was simulated with the SD model by varying three conditions. Three adoption scenarios were simulated, as follows:

1. no adoption of collaborative PLM and 3D TLS, reflecting “As-Is” conditions;

2. adoption by the four Navy shipyards; and
3. adoption by the four Navy shipyards plus three commercial shipyards.

Three product life spans were simulated: 5, 10, and 15 years. Three levels of cycle time reduction were simulated: 20%, 40%, and 60%. The resulting cost savings are shown in Table 4 and Figure 4.

Table 4. Simulated SHIPMAIN Cost Savings Due to Adoption of Collaborative PLM and 3D TLS

Shipmain Cost Savings (* $1,000,000)		Scale of Adoption and Cycle Time Reduction					
		4 yards, 20% CT reduction	4 yards, 40% CT reduction	4 yards, 60% CT reduction	7 yards, 20% CT reduction	7 yards, 40% CT reduction	7 yards, 60% CT reduction
Product Life	5 years	$776	$1,038	$1,559	$1,362	$1,819	$2,731
	10 years	$1,555	$2,076	$3,121	$2,726	$3,639	$5,465
	15 years	$2,333	$3,116	$4,680	$4,091	$5,461	$8,199

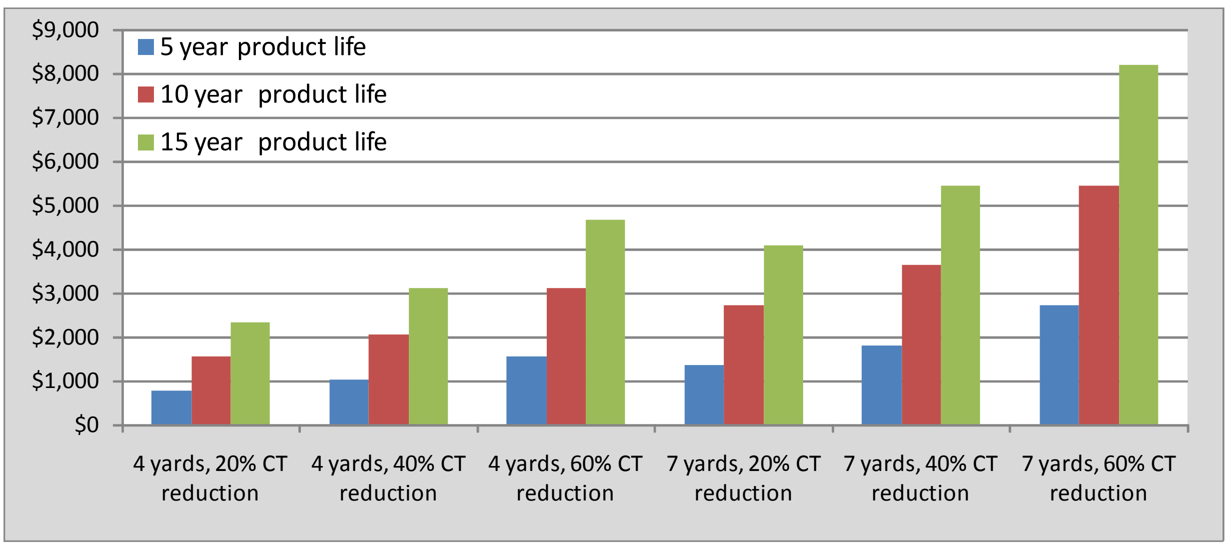

Figure 4. Simulated SHIPMAIN Cost Savings ($millions) Due to Adoption of Collaborative PLM and 3D TLS

Net estimated cost savings potential by adopting collaborative PLM and 3D TLS is very large, ranging from $776 million to well over $8 billion. As expected, cost savings increase with the number of yards adopting collaborative PLM and 3D TLS, product life span, and the size of the reduction in cycle time.

Several modeling assumptions can create differences between estimated and actual cost savings. One of these assumptions is the amortization of the initial cost over the product life span and the amortization of the yard installation costs over a year. Paying these costs at the time of adoptions would reduce initial savings and increase savings later, relative to the simulated values. More importantly, sharing the use of these technologies with the design and construction of new ships would share their cost with those processes and significantly increase SHIPMAIN cost savings.

A second modeling assumption that can impact estimated savings concerns the volume of ships being altered. In the model, the volume is determined by the assumed steady state flow and impact of cycle time reduction. As documented and described by Komoroski (2005), ship alteration volumes can vary due to external events (e.g., war), fleet conditions, and other factors. Cycle time reductions cannot be accurately determined until the improved technologies are installed and operational. The range of simulated values is believed to reflect a realistic envelop of possible conditions. Finally, the model assumes that all of the yards that adopt the technology adopt it at the same time and fully capture its benefits immediately. In practice, there might be a rolling out of collaborative PLM and 3D TLS, beginning in one or more years to learn how to best exploit its capabilities, followed by wider adoption by other shipyards. In total, these differences between practice and the modeling assumptions are expected to reduce savings, particularly early in adoption. Additional models can relax these assumptions and generate more detailed savings profiles. Regardless, the size of the potential savings justifies the adoption of collaborative PLM and 3D TLS.

Integrated Risk Management Analysis: Strategic Real Options

The results for the IRM analysis will be built on the quantitative estimates provided by the KVA+SD analysis. The IRM will provide a defensible quantitative risk analytics and portfolio optimization suggesting the best way to allocate limited resources to ensure the highest possible cost savings over time in ship maintenance processes. The first step in real options is to generate a strategic map through the process of framing the problem. Based on the overall problem identification occurring during the initial qualitative management screening process, certain strategic options would have become apparent for each particular project. The strategic options may include among other things, the option to expand, contract, abandon, switch, choose, and so forth.

Through the use of Monte Carlo simulation, the resulting stochastic KVA ROK model will have a distribution of values. Thus, simulation models, analyzes, and quantifies the various risks of each project. The result is a distribution of the ROKs and the project's volatility. In real options, we assume that the underlying variable is the future benefit minus cost of the project. An implied volatility can be calculated through the results of a Monte Carlo simulation performed. Usually, the volatility is measured as the annualized standard deviation of the logarithmic relative returns on the free net benefit stream.

Portfolio optimization is the next step in the analysis. If the analysis is done on multiple projects or processes, decision-makers should view the results as a portfolio of rolled-up projects because the projects are in most cases correlated with one another, and viewing them individually will not present the true picture. As organizations do not only have single projects, portfolio optimization is crucial. Given that certain projects are related to others, there are opportunities for hedging and diversifying risks through a portfolio. Because firms have limited budgets, along with time, people, and resource constraints, while at the same time have requirements for certain overall levels of returns, risk tolerances, and so forth, portfolio optimization takes into account all these to create an optimal portfolio mix. The analysis will provide the optimal allocation of investments across multiple projects.

Risk analysis assumes that the future is uncertain and that decision-makers have the right to make midcourse corrections when these uncertainties become resolved or risks distributions become known; the analysis is usually done ahead of time and thus, ahead of such uncertainty and risks. Therefore, when these risks become known, the analysis should be revisited to incorporate the information in decision making or revising any input assumptions. Sometimes, for long-horizon projects, several iterations of the real options analysis should be performed, where future iterations are updated with the latest data and assumptions. Understanding the steps required to undertake an integrated risk analysis is important because it provides insight not only into the methodology itself, but also into how it evolves from traditional analyses, showing where the traditional approach ends and where the new analytics start.

Real options analysis will be performed to determine the prospective value of the basic options over a multi-year period using KVA data as a platform. The strategic real options analysis is solved using various methodologies, including the use of binomial lattices with market replicating portfolios approach and backed up using a modified closed-form sequential compound option model. The value of a compound option is based on the value of another option. That is, the underlying variable for the compound option is another option, and the compound option can either be sequential in nature or simultaneous. Solving such a model requires programming capabilities.

For instance, we first start by solving for the critical value of *I,* an iterative component in the model using

$$X_2 = Ie^{-q(T_2-t_1)}\Phi\left(\frac{\ln(I/X_1)+(r-q+\sigma^2/2)(T_2-t_1)}{\sigma\sqrt{(T_2-t_1)}}\right) - X_1e^{-r(T_2-t_1)}\Phi\left(\frac{\ln(I/X_1)+(r-q-\sigma^2/2)(T_2-t_1)}{\sigma\sqrt{(T_2-t_1)}}\right)$$

Then, solve recursively for the value *I* above and input it into the model:

$$\begin{aligned} Compound\ Option &= Se^{-qT_2}\Omega\left[\begin{array}{l}\dfrac{\ln(S/X_1)+(r-q+\sigma^2/2)T_2}{\sigma\sqrt{T_2}};\\ \dfrac{\ln(S/I)+(r-q+\sigma^2/2)t_1}{\sigma\sqrt{t_1}};\sqrt{t_1/T_2}\end{array}\right] \\ &- X_1e^{-rT_2}\Omega\left[\begin{array}{l}\dfrac{\ln(S/X_1)+(r-q+\sigma^2/2)T_2}{\sigma\sqrt{T_2}}-\sigma\sqrt{T_2};\\ \dfrac{\ln(S/I)+(r-q+\sigma^2/2)t_1}{\sigma\sqrt{t_1}}-\sigma\sqrt{t_1};\sqrt{t_1/T_2}\end{array}\right] \\ &- X_2e^{-rt_1}\Phi\left[\frac{\ln(S/I)+(r-q+\sigma^2/2)t_1}{\sigma\sqrt{t_1}}-\sigma\sqrt{t_1}\right] \end{aligned}$$

The model is then applied to a sequential problem where future phase options depend on previous phase options (e.g., Phase II depends on Phase I’s successful implementation).

The variables are defined as follows:

S present value of future cash flows ($)

r	risk-free rate (%)
σ	volatility (%)
Φ	cumulative standard-normal
q	continuous dividend payout (%)
I	critical value solved recursively
Ω	cumulative bivariate-normal
X_1	strike for the underlying ($)
X_2	strike for the option on the option ($)
t_1	expiration date for the option on the option
T_2	expiration for the underlying option

The closed-form differential equation models above are then verified using the risk-neutral market-replicating portfolio approach assuming a sequential compound option. In solving the market-replicating approach, we use the following functional forms (Mun, 2005):

- Hedge ratio *(h)*: $h_{i-1} = \dfrac{C_{up} - C_{down}}{S_{up} - S_{down}}$
- Debt load *(D)*: $D_{i-1} = S_i(h_{i-1}) - C_i$
- Call value *(C)* at node *i*: $C_i = S_i(h_i) - D_i e^{-rf(\delta t)}$
- Risk-adjusted probability *(q)*: $q_i = \dfrac{S_{i-1} - S_{down}}{S_{up} - S_{down}}$

  obtained assuming $S_{i-1} = q_i S_{up} + (1 - q_i) S_{down}$

  This means that $S_{i-1} = q_i S_{up} + S_{down} - q_i S_{down}$,

  and $q_i [S_{up} - S_{down}] = S_{i-1} - S_{down}$,

  so we get $q_i = \dfrac{S_{i-1} - S_{down}}{S_{up} - S_{down}}$.

Integrated Risk Management Analysis: Portfolio Optimization

Modern Portfolio Theory (MPT) was introduced by Harry Markowitz with his paper “Portfolio Selection,” which appeared in the *Journal of Finance* (1952). He demonstrated that a portfolio of individual securities composed of consistently good risk–reward characteristics (e.g., stocks of all rail companies), could well be foolish. He detailed the mathematics of diversification, which focused on selecting portfolios based on their overall risk–reward characteristics. He felt that investors should create portfolios of dissimilar securities rather than purchase and hold only individual securities (e.g., only shares of IBM). Portfolio theory provides a broad context for understanding the interactions of systematic and non-systematic risk and reward.

Portfolio optimization is the analytical technique of allocating scarce resources (limited budget, time, cost, human resources, and program requirements) to satisfy and maximize strategic objectives, or determining how to best spend limited dollars to obtain the best or optimal outcome. Portfolio optimization also provides tools for organizing and managing a set of projects in a portfolio of projects to meet its goal (Mun, 2010). Portfolio management begins with an enterprise-level identification and definition of market opportunities and then prioritization of those opportunities within resource constraints (GAO, 2007, p. 9). A set of projects tracked across the entire portfolio in a timely and effective manner helps senior leadership make sound decisions, data-based decisions supported by analysis of cost, schedule, and performance risks. These future projects will have a national strategic impact as situations and partners change. The ability of senior leadership to adjust portfolios to meet defense needs now and in the future is critical.

Portfolio optimization is used by businesses to measure everything from money to performance. In the finance industry, it is used to measure the strength of a group of investments to make appropriate tradeoffs of expected return on investment and risk. Using the Markowitz Efficient Frontier (MVO, 2009), a ratio of the expected return for each asset, the standard deviation of each asset's logarithmic relative returns (measure of risk), and the correlation matrix between these assets, sets of portfolios with expected returns greater than any other with the same or lesser risk, and lesser risk than any other with the same or greater return could be identified (MVO, 2009). In the Information Technology (IT) sector, portfolio optimization is used as follows:

> Portfolio optimization is used to manage priorities for resource allocation. Based on limited resources (budget), which projects should we keep while increasing profits and which are failing to perform and losing money? Whatever is being measured during the analysis, it is a key factor in the success or failure of the business. Companies commonly use Net Present Value (NPV) analysis, which can show, in today's dollars, the relative cash flow of various alternatives over a long period of time. (GAO, 2007, p. 15)

In general, successful companies take a disciplined approach to prioritizing needs and initiating a balanced mix of executable development programs (GAO, 2007, p. 7). They begin with an enterprise level approach to identifying market opportunities and then prioritize them based on strategic goals, resources available, and risk. The market opportunities with the greatest potential to succeed are included in the portfolio.

So why is portfolio optimization important today? The Clinger-Cohen Act of 1996 mandates its use for all federal agencies. The GAO's "Assessing Risk and Returns: A Guide for Evaluating Federal Agencies' IT Investment Decision-Making," Version 1, (GAO, 1997) requires that IT investments apply ROI measures. DoD Directive 8115.01 (DoD, 2005a), issued October 2005, mandates the use of performance metrics based on outputs, with ROI analysis required for all current and planned IT investments. DoD Directive 8115.02 (DoD, 2006) implements policy and assigns responsibilities for the management of DoD IT investments as portfolios within the DoD Enterprise, where they defined a portfolio to include outcome performance measures and an expected ROI. The DoD Risk Management Guidance Acquisition guide book requires that alternatives to the traditional cost estimation be considered, because legacy cost models tend not to adequately address costs associated with information systems or the risks associated with them (Mun & Housel, 2006, p. 1). The CJCSI 8410.01 (CJSC, 2007) establishes policies and procedures for the Warfighting Mission Area Information Technology Portfolio Management and net-centric data sharing processes.

Over the next several years, the DoD plans to invest $1.4 trillion in major weapons system programs. Continued failure to deliver weapons systems on time and within budget not only delays providing critical capabilities to the warfighter, but results in less funding for other DoD and federal needs (GAO, 2007, p. 1). With this level of spending and an upcoming reduction in DoD obligation, it is important for the DoD to spend its money as efficiently as possible. This can only be accomplished by better evaluating the programs/systems for risk before they start being funded to truly ascertain their overall value toward meeting the strategic goals of the U.S. These programs contain considerable risks in the form of cost overruns, schedule delays, and performance failures.

So, what is the DoD currently doing? The DoD is using individual program managers to manage specific programs/systems, without regard to the overall strategic goal of the U.S. Each program is its own entity, with little or no interaction with other programs, and program managers are not held responsible for minimizing the risks associated with their particular programs. The DoD's service-centric structure and fragmented decision-making processes are at odds with the integrated, portfolio management approach used by successful commercial companies to make enterprise-level investment decisions (GAO, 2007, p. 18).

In 2004, the Defense Finance and Accounting Service (DFAS) implemented portfolio management in an effort to help prioritize initiatives and more closely link budget to agency strategy, while answering a presidential call for improving financial management. In doing this, they developed an approach which not only governs technology investments but includes all high-value initiatives ($250,000 or more). As a decision-making tool, Portfolio Management requires essential data about all initiatives to be entered into a central database and requires those initiatives to be scored against basic criteria and risk (decision analysis). Portfolio Management treats existing and new initiatives as assets to be managed instead of costs. The process is dynamic and iterative so that the portfolio reflects changing agency goals and priorities. The key to assessing portfolio effectiveness is measuring the right things. Because of the importance of performance measures in completing the portfolio requirements, it is crucial for DFAS to agree on the appropriate measures early in the Portfolio Management process.

Discussion and Conclusions

The KVA+SD+IRM framework for modeling and evaluating DoD systems was applied to the adoption of collaborative and 3D TLS in SHIPMAIN processes. The model extends the previous KVA modeling by including important implementation costs and improvements in performance due to cycle time reduction and a potential increase in ship yard maintenance capacity. Simulations across a range of values for uncertain conditions describe a defensible range of potential savings. The net estimated savings are substantial compared with the current approach to ship maintenance, from $776 million, if four yards adopt the improvements for five years and reduce average cycle time by 20%, to well over $8 billion, if all seven yards adopt the improvements over 15 years and reduce cycle time by 60%.

Conclusions From the Work

The approach to estimating the potential impact of adopting the collab-PLM + 3D TLS technologies on ship maintenance costs indicate that very large cost savings are possible. And, although some modeling assumptions may not become realities in terms of implementation strategies and conditions, the results of the current work provide a means to analyze the potential impacts of the adoption of collab-PLM + 3D TLS in the SHIPMAIN process in terms of cost savings.

Implications for Acquisition Practice

The current study is the fourth attempt to gauge the impact of these technologies and confirms the general results of the previous three studies: adopting these technologies will result in substantial cost savings and productivity increases. Further, the current study also provides a practical means to track the performance of these technologies over time allowing a continuous portfolio optimization based on learning about the performance of these technologies in ship maintenance over time.

Limitations of the Current Study

The primary limitation of the current study is the absence of ship maintenance performance data over time. Without this kind of performance information, it becomes very difficult to reassess and restructure maintenance resource portfolio allocations. The use of systems dynamics provides a means to make reasonable estimates based on a model that allows variation in initial conditions. The fact that the current study model mirrored the prior study's (Komoroski et al., 2005) empirically derived results provides some compelling evidence that the results of the SD modeling provide a defensible forecast of the cost saving impacts of these technologies. However, real historical performance data would provide the best means for forecasting the future cost savings and portfolio optimization impacts of these technologies on ship maintenance.

Next Steps: Portfolio Optimization and Efficient Frontier Analysis

The follow up analysis that will be included in the final report includes applying portfolio optimization in generating efficient portfolios and an investment efficient frontier. As discussed earlier, optimization is the process of iteratively finding the best combination of projects, processes, and decisions that will maximize a portfolio's total outcome or objective. Running the optimization procedure will yield an optimal portfolio of projects where the constraints are satisfied. This represents a single optimal portfolio point on the efficient frontier, for example, Portfolio B on the chart in Figure 5. Then, by subsequently changing some of the constraints, for instance, by increasing the budget and allowed projects, we can rerun the optimization to produce another optimal portfolio, given these new constraints. Therefore, a series of optimal portfolio allocations can be determined and graphed. This graphical representation of all optimal portfolios is called the Portfolio Efficient Frontier. At this juncture, each point represents a portfolio allocation; for instance, Portfolio B might represent projects 1, 2, 5, 6, 7, 8, 10, 15, and so forth, while Portfolio C might represent projects 2, 6, 7, 9, 12, 15, and so forth, each resulting in different tactical, military, or comprehensive scores, and portfolio returns.

It is up to the decision-maker to decide which portfolio represents the best decision, and if sufficient resources exist to execute these projects. Typically, in an Efficient Frontier analysis, you would select projects where the marginal increase in benefits is positive, and the slope is steep. In the next example, you would select Portfolio D rather than Portfolio E, as the marginal increase is negative on the y-axis (e.g., Tactical Score). That is, spending too much money may actually reduce the overall tactical score, and hence this portfolio should not be selected. Also, in comparing Portfolios A and B, you would be more inclined to choose B, as the slope is steep, and the same increase in budget requirements (x-axis) would return a much higher percentage Tactical Score (y-axis). The decision to choose between Portfolios C and D would depend on available resources and the decision-maker deciding if the added benefits warrant and justify the added budget and costs.

Budget	Comprehensive Score	Tactical Score	Military Score	Allowed Projects	ROI-RANK Objective
$3,800	33.15	62.64	58.58	10	$470,236
$4,800	36.33	68.85	66.86	11	$521,646
$5,800	38.40	70.46	75.69	12	$623,558
$6,800	39.94	72.14	82.31	13	$659,948
$7,800	39.76	70.05	86.54	14	$676,280

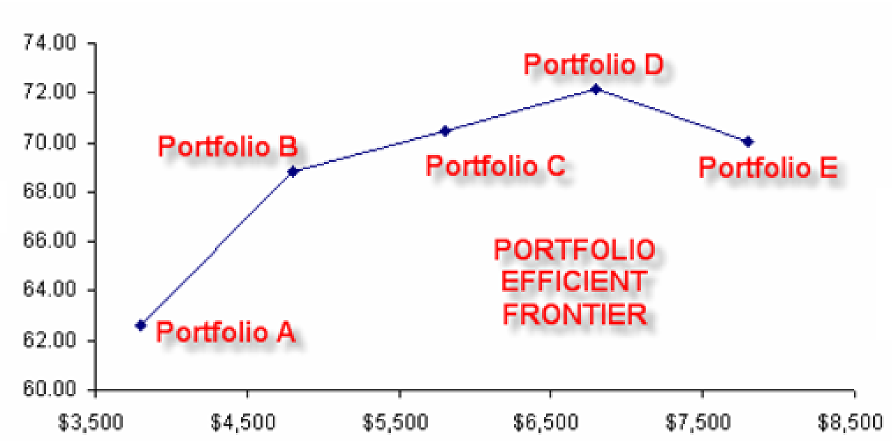

Figure 5. Efficient Frontier Example

To further enhance the analysis, you can obtain the optimal portfolio allocations for C and D, and then run a simulation on each optimal portfolio to decide what the probability that D will exceed C in value is, and whether this probability of occurrence justifies the added costs.

For the next steps in this study, the current research portfolio optimization and MPT will be applied at several levels, from the macro level to the micro level. The final results of the MPT optimization will be included in the final report to the Acquisition Program and will be available through the NPS Acquisition Program.

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