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

20 September 2011

by

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Abstract

The current cost-constrained environment within the federal government and Department of Defense (DoD) requires a cogent approach to cost reductions that will not compromise the productivity of core defense support processes such as ship maintenance, a core process that is central to naval operations. The SHIPMAIN initiative was designed to standardize ship maintenance alternations in order to take advantage of the cost savings from standardizing core processes. A problem in using the SHIPMAIN approach has been that the normal cost-reduction learning curve for common ship alterations, across a series of common ship platforms, has not materialized. 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 available by moving to a ship maintenance approach that incorporates the 3D TLS and collab-PLM tool suite. Results suggest that when the SHIPMAIN process employs 3D terrestrial laser scanning (3D TLS) and collaborative product lifecycle management (collab-PLM) tools, SHIPMAIN will finally obtain the prophesized learning curve benefits. The results indicated that the biggest "bang for buck" is in using the combination of the two technologies. Results of the KVA and SD scenario analysis provided the financial information required to forecast an optimized portfolio controlling for risk using the IRM methodology and tool suite. Results indicate that both rapid and incremental implementation approaches generate significant savings and that other factors should be incorporated into final implementation of the 3DTLS + collab-PLMtool tools.

Keywords: Knowledge value added, simulation modeling, portfolio optimization, real options, risk management, technology adoption

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Dr. Tom Housel specializes in valuing intellectual capital, knowledge management, telecommunications, information technology, value-based business process reengineering, and knowledge value measurement in profit and non-profit organizations. He is currently a tenured Full Professor for the Information Sciences (Systems) Department. He has conducted over 80 knowledge value added (KVA) projects within the non-profit, Department of Defense (DoD) sector for the Army, Navy, and Marines. He also completed over 100 KVA projects in the private sector. The results of these projects provided substantial performance improvement strategies and tactics for core processes throughout the DoD organizations and the private sector companies. He has managed a $3Mil+ portfolio of field studies, educational initiatives, and industry relationships. His current research focuses on the use of KVA and “Real Options” models in identifying, valuing, maintaining, and exercising options in military decision making. Prior to joining NPS, he also was a Research Fellow for the Center for Telecommunications Management and Associate Professor at the Marshall School of Business at the University of Southern California. Tom has been the Chief Business Process Engineer for Pacific Bell, where he completed numerous reengineering projects and developed a the KVA methodology that objectively measures the value-added by process reengineering. His last assignment in the corporate world was as the Chief of Consumer Market Research for Telecom Italia in Venice, Italy where he developed new methods for predicting the adoption rates for new interactive multimedia broadband applications. He is Managing Partner for Business Process Auditors, a firm that specializes in training Big Six consultants, large manufacturing and service companies in the Knowledge Value-Added methodology for objectively measuring the return generated by corporate knowledge assets/intellectual capital. He received his Ph.D. from the University of Utah in 1980. He won the prestigious Society for Information Management award for best paper in the field in 1986. 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 vol 2 2005). His latest books include: “Measuring and Managing Knowledge” and “Global Telecommunications Revolution: The Business Perspective” with McGraw-Hill (both in 2001).

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List of Abbreviations and Acronyms

3D	THREE DIMENSIONAL
3D TLS	3D TERRESTRIAL LASER SCANNING SYSTEM
AFOM	ALTERATION FIGURE OF MERIT
ALT	ACTUAL LEARNING TIME
ASE	ADVANCED SHIPBUILDING ENTERPRISE
C5I	COMMAND, CONTROL, COMMUNICATIONS, COMPUTERS, COMBAT SYSTEMS AND INTELLIGENCE
CAD	COMPUTER-AIDED DESIGN
CBA	COST BENEFIT ANALYSIS
CM	CONFIGURATION MANAGEMENT
CUO	COMMON UNITS OF OUTPUT
DoD	DEPARTMENT OF DEFENSE
DoN	DEPARTMENT OF THE NAVY
DP	DECISION POINT
FMP	FLEET MODERNIZATION PLAN
FY	FISCAL YEAR
IEDP	IMPROVED ENGINEERING DESIGN PROGRAM
ILS	INTEGRATED LOGISTICS SUPPORT
IRM	INTEGRATED RISK MANAGEMENT
IT	INFORMATION TECHNOLOGY
KVA	KNOWLEDGE VALUE ADDED
KVA+RO	KNOWLEDGE VALUE ADDED PLUS REAL OPTIONS
L6S	LEAN SIX SIGMA
NAVSEA	NAVAL SEA SYSTEMS COMMAND
NDE	NAVY DATA ENVIRONMENT
NPS	NAVAL POSTGRADUATE SCHOOL
NSRP	NATIONAL SHIPBUILDING RESEARCH PROGRAM
OPNAV	OFFICE OF THE CHIEF OF NAVAL OPERATIONS
PLM	PRODUCT LIFECYCLE MANAGEMENT

RCP	RECOMMENDED CHANGE PACKAGE
RLT	RELATIVE LEARNING TIME
ROI	RETURN IN INVESTMENT
ROK	RETURN ON KNOWLEDGE
SC	SHIP CHANGE
SCD	SHIP CHANGE DOCUMENT
SD	SYSTEMS DYNAMICS
SES	SENIOR EXECUTIVE SERVICE
SHIPMAIN	SHIP MAINTENANCE
SHIPMAIN EP	SHIP MAINTENANCE ENTITLED PROCESS
SIS	SPATIAL INTEGRATED SYSTEMS
SME	SUBJECT-MATTER EXPERT
SPAWAR	SPACE AND NAVAL WARFARE SYSTEMS COMMAND
SSCEPM	SURFACE SHIP AND CARRIER ENTITLED PROCESS FOR MODERNIZATION
TOC	TOTAL OWNERSHIP COST
TYCOM	TYPE COMMANDER

I. Executive Summary

The current cost-constrained environment within the federal government and Department of Defense (DoD) requires a cogent approach to cost reductions that will not result in compromising the productivity of core defense support processes such as ship maintenance. 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) that was designed to standardize ship maintenance alternations in order to take advantage of the cost savings from standardizing core processes. One purpose of SHIPMAIN was to take advantage of the well documented cost-savings learning curve found in the manufacturing arena. A problem in using the SHIPMAIN approach has been that the normal cost-reduction learning curve for common ship alterations, across a series of common ship platforms, has not materialized. Figure 1 provides a notional picture of this phenomenon.

The results of the current study suggest that when the SHIPMAIN process employs 3D terrestrial laser scanning (3D TLS) and collaborative product lifecycle management (collab-PLM) tools, SHIPMAIN will finally obtain the prophesized learning curve benefits. The study also demonstrates the potential value of each of these tools individually and in combination. The results indicated that the biggest “bang for buck” is in using the combination of the two technologies.

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 available by moving to a ship maintenance approach that incorporates the 3D TLS and collab-PLM tool suite. 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-saving learning curve.

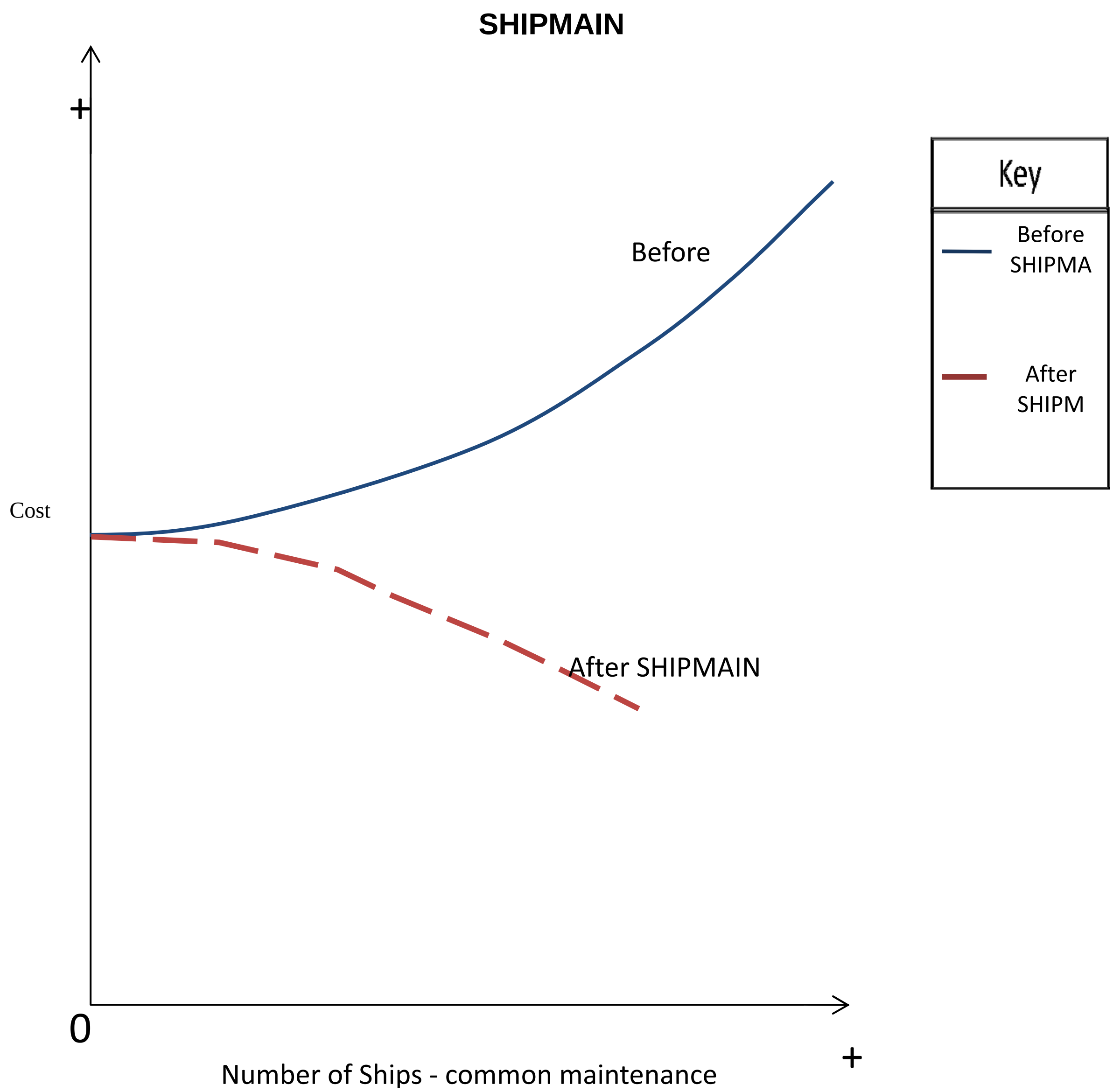

Figure 1. Learning Curve Before and After SHIPMAIN Adoption

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, 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 are currently employed in ship building. When they are also incorporated into the maintenance cycle, the results 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 created, updated, and distributed remotely, cross platform sharing of these images, and the capability for cross platform searches). Using the tools across the entire ship building and maintenance lifecycle should result in substantial cost savings and increased shipyard capacity to accommodate the Secretary of the Navy’s (Honorable Ray Mabus) goal of a large increase in the fleet.

To evaluate and select ship maintenance options (e.g., strategies for the 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.[1] In addition to

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[1] In acquisition contracts collab- PLM is commonly identified within the Integrated Data Environment (IDE) or Integrated Product Development Environment (IPDE). The collab-PLM tool maintains the critical data relationships across a variety of applications that are pervasive throughout the entire lifecycle of the ship (acquisition through sustainment). Transferring the data temporarily or permanently outside of the OEM's PLM tool causes the data relationships to become disarrayed and out of date (e.g., a configuration management problem) which results in a static out-of-date representation of the data. Also, transferring data outside of the OEM's PLM tool produces no more than the electronic storage and retrieval of paper drawings that have been the root cause of many previous in-service functional challenges (i.e., the primary reason for ship checks). The Navy's investment in the OEM's PLM tool maintains the digital cognitive relationships across a ship, a ship

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 for ship maintenance processes. This will allow acquisition professionals to develop ways to mitigate these risks by taking advantage of the most promising strategic ship maintenance options, while analytically developing and allocating budgets to optimize project portfolios.

The Naval Postgraduate School (NPS) employed the Knowledge Value Added + Systems Dynamics + Integrated Risk Management (KVA+SD+IRM) valuation framework to address these issues. Once the technologies are in place and historical data becomes available, the KVA+SD+IRM approach will provide even higher fidelity analysis and identification of the most promising strategic investments in ship maintenance core process options.

In this study, the KVA+SD+IRM framework is used to quantify and project potential process cost savings and the potential benefits of selecting collab-PLM + 3D TLS technology in the ship maintenance 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 ship maintenance.

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

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class, and across the lifecycle. This critical relationship has to be carried forward from ship building to the ship maintenance, sustainment and modernization operations to fully benefit from the collab-PLM technology investment.

of the KVA and SD scenario analysis were used to perform a real options analysis and future research will incorporate portfolio optimization using modern portfolio theory (MPT).

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II. KVA+SD+IRM Framework

The Knowledge Value Added + Systems Dynamics + Integrated Risk Management (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 ship maintenance process improvements with collaborative product lifecycle management + 3D terrestrial laser scanning (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 a more realistic portfolio evaluation of the technologies in terms of risks while taking into account uncertainty in estimating future benefits.

The benefits of this framework include the following:

- Supplies high fidelity models of potential cost savings as well as the 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 (1996); Nunn–McCurdy Breach) 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 acquisition 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.

III. 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 ship maintenance (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[2] and three decision points (DP)[3] 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, pp. 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.

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[2] Five Phases: I—Conceptual, II—Preliminary Design, III—Detailed Design, IV—Implementation, V—Installation (Commander, Naval Sea Systems Command, 2006).

[3] 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).

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 FY2004 in order to

- increase the efficiency of the maintenance and modernization process without compromising its effectiveness,
- define a 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.

The current study examines the potential cost savings and productivity improvements that would feed an IRM 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.

IV. 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 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). Sales of terrestrial 3D 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[4] 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.

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

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V. 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 alternation 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, dissemination, and use of product definition information across the extended enterprise, from concept to end of life (CIMdata, 2007a).[5] 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[6]. Figure 2 indicates the evolution of PLM

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[5] 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).

[6] The two largest US shipyards, who construct aircraft carriers and submarines are also transitioning into collab-PLM solutions. Typically PLM vendors do not focus efforts on the shipbuilding industry, because of its size relative to other products such as Automotive or Aerospace. Having a PLM tool designed specifically for an industry has a significant impact on the tools efficiency within that industry.

applications, illustrating their stages before reaching the “plateau of productivity” in the mainstream market.

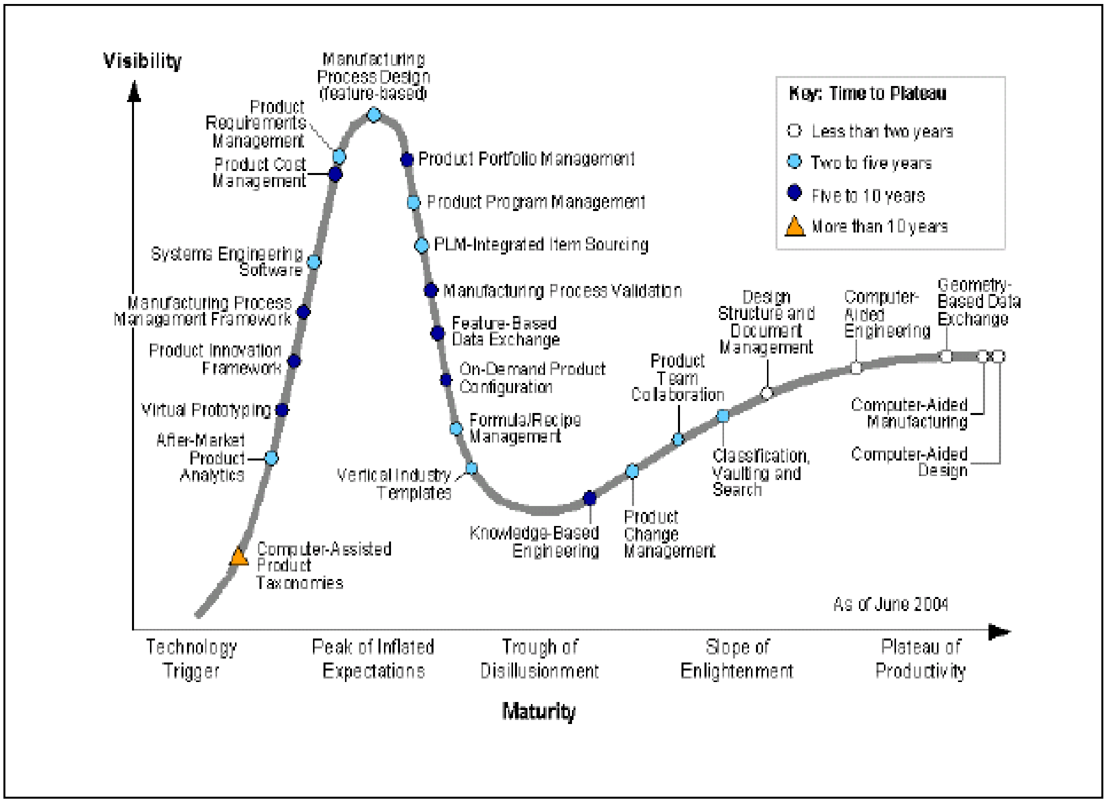

Figure 2. Evolution of PLM
(Halpern & Smith, 2004)

The assimilation of 3D TLS and collab-PLM technologies into Phases IV and V of SHIPMAIN could be a 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” (without the technologies) and “To-Be” (with the technologies) scenarios.

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

The KVA+SD+IRM valuation framework was used to demonstrate how the integration of these two technologies within Phase IV of SHIPMAIN can result in substantial cost savings and decreased fleet cycle-time via significant productivity improvements. The results also demonstrate the possible increases in shipyard capacity when these tools are used in ship maintenance. This may become a critical benefit for the Navy per the Secretary of Navy's recently articulated goal for a substantial long-term increase in the fleet's size.

A prior study of the ship maintenance process (Komoroski, 2005) was used as a basis for the current work. That study identified seven sequential core processes, as well as the subprocesses within each core process, that are utilized to plan for ship maintenance alterations on U.S. Navy surface ships, shown in Figure 3. The study collected data from the Puget Sound Planning Yard through extensive interviews with subject matter experts. This data was used to quantitatively describe ship maintenance in an "As-Is" environment, i.e. without collab-PLM + 3D TLS technologies. The KVA method was applied to model the "as-is" environment, which as used as baseline cost and productivity data for the current work.

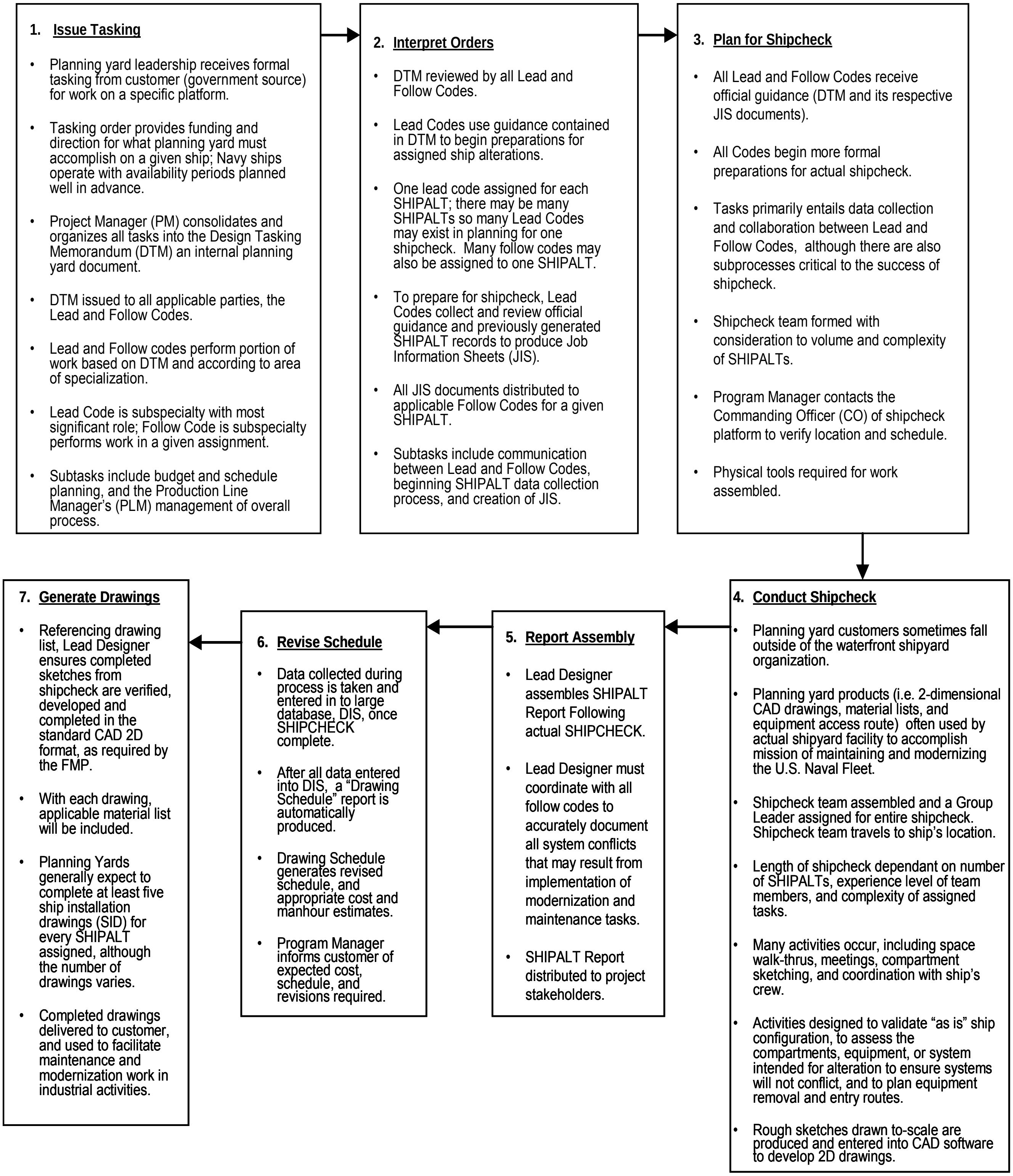

Figure 3. Planning Yard Core Processes
(Komoroski, Housel, Hom, and Mun 2006, p. 38)

The Komoroski study estimated baseline costs for these Shipmain Phase Four seven core processes to be $45 million per year.[7] This estimate was based on executing the seven core planning processes 40 times across the four public shipyards. The model was then used to model costs in a “To-Be” environment in which 3D TLS had been adopted by the four shipyards. Adding 3D TLS to the planning process cycle lowered expenses a projected 84% (to less than $8 million), as seen in Table 1. Introduction of 3D TLS in the “To-Be” environment could result in projected cost savings of nearly $37 million because Subprocesses 3, 4, and 7 were dramatically re-engineered (Komoroski, et.al., 2006).

The second notional “To-Be” KVA model evaluated the effects of adding both 3D TLS and the collab-PLM suite of software to the “As-Is” baseline. Projections for this scenario (based on increased savings in core processes 3, 4, and 7, as well as additional savings realized in core processes 2 and 5, included a cost savings of 90%, or approximately $40 million.

Table 1. Table 1. KVA Results—Analysis of Costs of Seven Core Planning Processes

(Komoroski et al., 2006, p. 36)

Seven Core Processes	**Cost**
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**

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

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VII. KVA Results

The cost analysis results were based on the “As-Is” KVA baseline analysis from the previous study. The return on investment (ROI) for each of the seven core processes was calculated (Table 2). The numerator of the ROI calculation was the difference between the surrogate revenue (based on common units of output for each process) per time period for each process and the cost of the process, divided by the cost for the process (ROI = (Revenue per process-Cost for the process)/Cost for the process). These estimates provided baseline relative productivities for each of the core processes. For example, process 3 – Plan for Ship Check, provided the lowest ROI (-99%) even though it was not the most costly. And process 7, clearly the most costly ($39,386,000 from Table 1), was not the least productive process in terms of its ROI performance (-37%, 5th of the seven core processes). These baseline estimates provide a reference point for comparing relative productivity increases when the technologies are included in the process modeling, which results in substantial increases in the two “To-Be” ROI estimates.

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 current study's SD model. A comparison with the SD model and the static KVA analysis revealed that the SD model was of high fidelity with the previous results and could be used for further analysis and projections for the "To-Be" scenarios. These analyzes can describe a variety of environmental conditions, such as different product lifespans, thereby capturing the potential effects of the two technologies on resulting costs and ROIs. While these results of the previous study might be considered relatively positive, the current work reveals that the addition of collab-PLM + 3D TLS technologies promise to return even more significant savings and higher ROIs.

VIII. 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 seven 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 28 subprocesses were aggregated for the current cost savings estimates. Analysis at the seven core processes and 28 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 or the capacity of the yard to handle more ships increases, 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 were not included in the previous work. However these factors can significantly impact cost savings and were therefore incorporated into the current SD model. Model improvements that impacted benefits include the following:

- Variation in the number of ships that are in the process of adopting of collab-PLM + 3D TLS in larger numbers of shipyards;

- Increase in number of ships that can be processed through the yards if collab-PLM + 3D TLS are adopted due to the reduced cycle-time of individual ships with collab-PLM + 3D TLS; and
- Life span of the use of collab-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)[8] 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:

$$\boldsymbol{\Pi} = \boldsymbol{\upsilon\lambda}$$

where,

π = cost savings {$}

ʋ= number of benefits generated {common units of output}

λ = unit cost savings {$/common unit of output}

In other words, the cost savings is equal to the volume of benefits generated, measured with the number of common units of output, multiplied by the unit cost savings, measured with the average dollars required to generate a common unit of output. Volume of benefits generated is the number of common units of output (CUO) produced under the adoption ("To-Be") scenario. Unit cost savings are the

[8] Common units of output (CUO) are the measure of benefits developed in the Knowledge Value Analysis (KVA) methodology and reflect the amount of knowledge required to produce each unit of output for a sub-process.

difference between the unit cost without the technologies (As-Is conditions) and with the technologies (To-Be conditions), as follows:

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

λ_{wo} = denotes SHIPMAIN unit cost without collab-PLM + 3D TLS ("As-Is") scenario

λ_{w} = denotes SHIPMAIN unit cost with collab-PLM + 3D TLS ("To-Be") scenario

λ_{wo} = Process $Cost_{wo}$ / CUO $generated_{wo}$

λ_{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.

Initial System Costs = Software purchase and installation cost +

(3D TLS installation per yard cost) * (Yards adopting collab-PLM + 3D TLS).

The software purchase and installation cost (estimated to be $1.6 million) was amortized evenly over the product life span, assumed to be 5, 10, or 15 years. 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 = $\sum_{\text{Life span}}\sum_{\text{subprocesses}}$ (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 collab-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 were collected as part of the current research in spring of 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). Little's law says that, in equilibrium, the size of a completely mixed stock, the flow through the stock, and the average time required to process a unit of work are related as follows:

$$S = f * t.$$

Where, S – stock

f – flow through the stock

t – average time required to process a unit of work

Applying Little's law to the flow of ships through the shipyards creates

$$SY = TR * CT.$$

Where, SY – ships in the yards

TR – throughput rate of ships passing through the yards

CT – average cycle-time to process a ship

Using subscripts to identify the percent reduction in average cycle-time, the As-Is conditions are

$$SY_0 = TR_0 * CT_0$$

and the conditions with a 20% reduction in average cycle-time are

$$SY_{20} = TR_{20} * CT_{20} = TR_{20} * (80\% * CT_0).$$

Assuming that the capacity of the yards does not change and that the yards are fully utilized, $SY_0 = SY_{20}$. Therefore,

$$TR_0 * CT_0 = TR_{20} * (80\% * CT_0)$$

and

$$TR_{20} = TR_0 / 0.80 = 1.25\ TR_0 .$$

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.

If the adoption of collab-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. Similar calculations generate a 67% increase in throughput due to a 40% decrease in average cycle-time and a 150% increase in throughput due to a 60% reduction in average cycle-time. These factors (1.25, 1.67, and 2.50) were used in the model to reflect increased throughputs.

IX. 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. In addition, the estimated annual cost of operating four yards without adoption (As-Is conditions) as simulated using the SD model (=$45.63 million / year) is within 2% of the cost estimated for the same conditions by Komoroski, 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 collab-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

X. Collab-PLM and 3D TLS Adoption Conditions and Simulation Results and Discussion

SHIPMAIN was simulated with the SD model by varying four conditions: 1) the number of ship yards that adopt the technology, 2) the cycle time reduction due to the adoption of the technologies, 3) the life span of the technologies before they were replaced, and 4) the finance plan for adoption. The three simulated numbers of shipyards adopting were zero, which represents the As-Is conditions; four, which represents adoption by the Navy yards but not the commercial yards; and seven, which represents adoption by the four Navy yards and the three commercial yards. The three simulated levels of cycle-time reduction were 20%, 40%, and 60%, based on estimates of experience by other industries provided by the product vendor. Three product life spans were simulated: 5, 10, and 15 years (researcher estimates). Two financing plans were simulated, based on either adoption of the technologies by the four Navy yards over several years or the simultaneous adoption of those technologies by all four Navy yards. The first plan (adoption over several years) assumed that the Navy paid a total of $6,400,000 , based on an estimated $1,600,000 per Navy yard (vendor estimate) for each of the four Navy yards. The second financing plan (simultaneous adoption) assumed that the Navy paid a total cost of $3,200,000 for all four Navy yards. The 36 scenarios generated by the possible combinations of these adoption alternatives (2 yard adoption alternatives, 3 cycle time reductions, 3 life spans, 2 finance plans) were used to estimate ship maintenance cost.

The simulated costs with no yards adopting the technologies (As-Is conditions) over the product life spans assuming four or seven yards of production were used as base cases for estimating savings. As an example, the As-Is costs for four yards if the product lifespan is five years is estimated to be $228.15 million (=$45.63 million/year X 5 years). The difference between each simulated cost of an adoption scenario and the base case cost for the same number of yards and product life span is the estimated cost savings for the scenario. The resulting cost savings for each adoption scenario are shown in Table 4. For example, the estimated cost of four yards adopting the technologies for a 5 year life span and capturing 20% cycle time reduction with a cost of $1.6 million for the two technologies per yard is $39.05 million. Therefore estimated savings is $189.10 million (=$228.2 – 39.05), the value shown in the upper left estimated savings cell in Table 4.

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

Reduced Total Ownership Costs ($millions)											
Finance Plan: $1.6m for each of 4 yards = $6.4m total											
20% CT reduction	**Product Lifespan**			*40% CT reduction*	**Product Lifespan**			*60% CT reduction*	**Product Lifespan**		
No. Yards Adopting	**5 years**	**10 years**	**15 years**	**No. Yards Adopting**	**5 years**	**10 years**	**15 years**	**No. Yards Adopting**	**5 years**	**10 years**	**15 years**
4	189.10	384.59	580.08	**4**	179.73	365.87	552.01	**4**	**161.04**	328.48	495.92
7	337.96	682.34	1026.68	**7**	321.58	649.57	977.55	**7**	288.86	584.13	879.40
Finance Plan: $3.2m for 4 yards = $3.2m total											
20% CT reduction	**Product Lifespan**			*40% CT reduction*	**Product Lifespan**			*60% CT reduction*	**Product Lifespan**		
No. Yards Adopting	**5 years**	**10 years**	**15 years**	**No. Yards Adopting**	**5 years**	**10 years**	**15 years**	**No. Yards Adopting**	**5 years**	**10 years**	**15 years**
4	192.29	387.79	583.28	**4**	182.93	369.07	555.21	**4**	164.24	331.69	499.10
7	341.16	685.53	**1029.88**	**7**	341.16	652.77	980.75	**7**	324.78	588.94	884.23

Net estimated cost savings potential range, by adopting collab-PLM and 3D TLS, is from $161 million to $1.03 billion (in bold and underlined print in Table 4). As expected, cost savings increase with the number of yards adopting collab-PLM and 3D TLS and product life span.

Savings reduce with increased cycle-time reduction, a counterintuitive result. The impact of cycle-time reduction on the throughput of ships, described previously in the specification of the model on pages 23-25, explains this behavior because the increased throughputs increase costs, decreasing savings. For example, for 4 yards acquiring the two technologies for $1.6 million each (see the top row of Table 4) with a product life span of 10 years, savings dropped from $385 million to $366 million to $328 million as cycle time reduction increases from 20% to 40% to 60%.

The increased throughput capacity of the maintenance yards made available by the adoption of collab-PLM and 3D TLS may prove critical for Navy development. Navy Secretary Mabus recently announced plans to build a 324 warship Navy by 2020 (Howe, 2011). This will require increased ship maintenance capacity. The increased capacity may prove a critical part of growing the fleet without increasing the number of maintenance yards.

The modeling described above assumes that the Navy has the demand and other required resources needed to utilize the increased capacity created by reduced cycle-times. This may not be accurate, but describes an extreme condition on a continuum of potential combinations of increased throughput and decreased capacity. The other end of that continuum assumes that the throughput rate remains unchanged. Similar calculations to those above show that the required capacities with reduced cycle-times are proportionate to the cycle-time reduction. Therefore, a 20% cycle-time reduction for the current throughput requires 20% less capacity, and so forth. This scenario could allow the Navy to maximize capacity use at certain yards and idle or close one or more yards that were not needed, depending on the cycle-time reduction actually captured.

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 up front 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. For example, the Damen Shipyards approach uses collaborative PLM tools and these tools enable them to experience significant cost savings compared to where these tools have not been in use until recently.[9]

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 collab-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, but may exceed cost savings expectations in the longer run, once the learning curve is overcome. Additional models could relax these assumptions and generate more detailed savings profiles. Regardless, the size of the potential savings justifies the adoption of collab-PLM and 3D TLS, whether in the near or medium time frame. The IRM analysis further justifies this conclusion as the results will demonstrate.

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[9] A forthcoming study will compare Damen ship maintenance using collaborative PLM tools and US ship maintenance approaches that currently do not use these tools.

XI. Integrated Risk Management Analysis: Strategic Real Options

The results for the IRM analysis are built on the quantitative estimates provided by the KVA+SD analysis. The IRM analysis provides defensible quantitative risk analytics and portfolio optimization that suggest the best way to allocate limited resources to ensure the highest possible cost savings over time in ship maintenance processes. The first step in IRM using real options is to generate a strategic map through the process of framing the problem. Generally, problem identification during the initial qualitative management screening process leads to the identification of strategic options for each particular project. Those strategic options can include flexibility to, among other things, expand, contract, abandon, switch, and choose. The current work focuses on the use of real options to expand the adoption of -PLM and 3D TLS, including some options to abandon the adoption effort.

Through the use of Monte Carlo simulation, the stochastic KVA ROK model that is based on the identified options has a distribution of values for the drivers of project value. Thus, simulation models analyze and quantify the various risks of each project. The product of the simulations 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 the 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 will be performed in a future phase of the project because, as of now, there is insufficient data to perform an adequate portfolio optimization applying modern portfolio theory. A description of the proposed optimization approach is presented in the appendix. When the analysis is done on multiple projects or processes, decision-makers can 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 have only single projects, portfolio optimization becomes crucial. Given that certain projects are related to others, there are opportunities for hedging and diversifying risks through a portfolio. Because organizations have limited budgets, along with time, people, and resource constraints, and at the same time have requirements for certain overall levels of returns, risk tolerances, and so forth, portfolio optimization would take into account all these conditions to create an optimal portfolio mix. The analysis would provide guidance for identifying the optimal allocation of investments across multiple projects.

The current work addresses how the Navy can use real options to manage risk. Risk management using real options 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. Risk analysis for the design and use of real options is usually done ahead of time and, thus, ahead of actually experiencing such uncertainty and risks. Therefore, when these risks become known and better understood, the analysis should be revisited to incorporate new information into decision-making or to revise 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 was performed to determine the prospective value of the basic options over a multiyear period using KVA data as a platform. The strategic real options analysis is solved employing various methodologies, including the use of binomial lattices with a market-replicating portfolios approach, and backed up using a modified closed-form sequential compound option model. Risk analysis of the current work requires the modeling of compound options. Compound options occur when managers have an option to use a second option, or when an option is "nested" within a different option. 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 be either sequential in nature or simultaneous. Solving such a model requires programming capabilities. See Appendix for examples.

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XII. Integrated Risk Management Analysis: Analysis Results

Figure 4 shows the graphical depiction of the scenarios available for this initial 3D TLS and collab-PLM analysis. This figure uses a decision tree to depict the 2 alternate financing scenarios (Scenario 1 comprises a total of $6.4 million where $1.6 million per shipyard is implemented one at a time for a total of 4 shipyards, and Scenario 2 where all 4 shipyards are implemented simultaneously, with a total of $3.2 million); the 3 possible reductions in cycle-time (20%, 40%, and 60%); the 2 levels of implementation (4 yards or 7 yards); and the technology's life span (5 years, 10 years, and 15 years). We chose the decision tree for its simplicity in graphically depicting the various scenarios and conditions. In decision trees square nodes depict investment decisions such as how many yards to implement; circles depict uncertainty events such as cycle-time reduction and life span; and triangles indicate end points of all possible combinations of outcomes. In this case there are 36 possible combinatorial outcomes. The decision tree is only used for showing these various combinatorial outcomes and not used as a computational method due to its many limitations. Instead, we revert to using the Monte Carlo risk simulation and strategic real options methodologies discussed in the following sections.

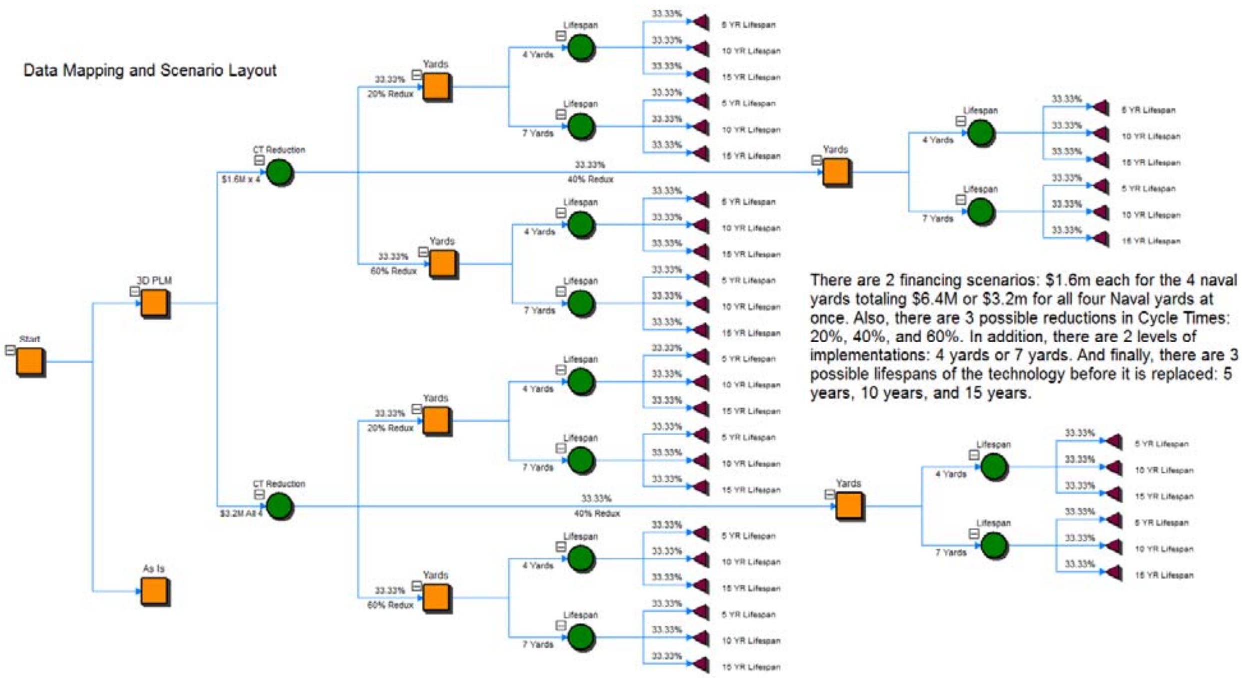

Figure 4. Representation of Implementation Scenarios and Data Requirements

Figure 5 shows the three investment option paths. The first strategy (Strategy A) is a phased implementation, where the first 4 yards are implemented sequentially, one at a time, and at the end of the fourth yard (Phase 4), an additional 3 yards can be implemented at once. The benefit of this first option is that a lower initial investment is at risk, and at any time, the entire project can be abandoned. That is, at the end of Phase 1 or during any of the phases, if significant problems arise during the implementation process, the Navy can decide to abandon the project altogether and not risk the entire investment amount (e.g., only $1.6 million will be expended in Phase 1 instead of risking a total of $3.2 million in implementing all 4 yards at once, or $7.2 million for all 7 yards). The disadvantage of this scenario is that the total ownership cost savings will not be realized as quickly as in Strategy B, where multiple yards are simultaneously implemented.

This second option path, or Strategy B, involves rapid implementation by investing in 4 yards simultaneously, thereby reducing the total investment cost ($3.2 million instead of $6.4 million as in Strategy A), but clearly the investment amount risked is higher. The benefit is that implementation is rapid and the savings can be obtained faster, and if all goes well with the implementation, the additional 3 yards can be added to the portfolio quickly.

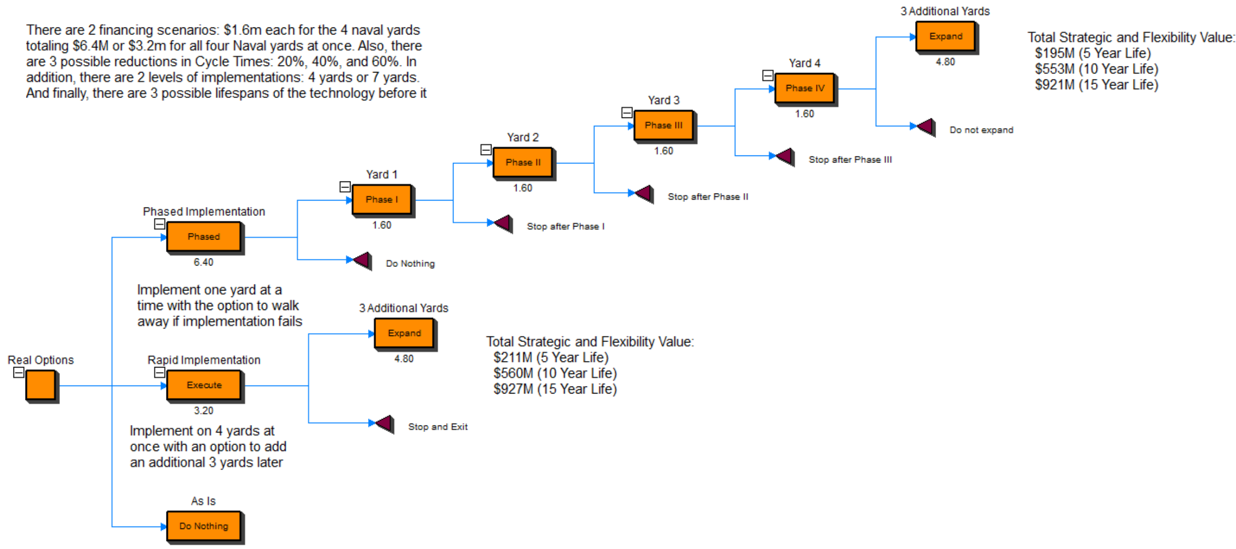

Figure 5. Strategic Real Options of Investment Paths

Both Strategies A and B are compared to Strategy C, the As-Is, or Do-Nothing-New, situation. Therefore, the analysis results from the strategic real options analysis is a relative analysis, where the results indicate reduction in total ownership costs and strategic values relative to Strategy C.

Figure 6 shows the various scenarios and the reduction in total ownership cost (TOC) savings. The table also shows the risk-adjusted, inflation-adjusted, and diminishing marginal returns adjusted savings, as well as their relative volatilities. These adjustments are required because the different implementation paths take on different timelines and, hence, have different inflation effects as well as risk-time effects. Further, we assumed some levels of diminishing marginal returns on the reduction in TOC over time, as will be discussed later.

TOC Savings ($millions)

Finance Plan: $1.6m for each of 4 yards = $6.4m total

20% CT reduction No. Yards Adopting	Product Lifespan 5 years	10 years	15 years
4	189.10	384.59	580.08
7	337.96	682.34	1026.68
4 ADJ	119.53	332.54	551.20
7 ADJ	213.63	589.99	975.56
Expansion	1.7872	1.7742	1.7699

40% CT reduction No. Yards Adopting	Product Lifespan 5 years	10 years	15 years
4	179.73	365.87	552.01
7	321.58	649.57	977.55
4 ADJ	113.61	316.35	524.53
7 ADJ	203.28	561.66	928.88
Expansion	1.7893	1.7754	1.7709

60% CT reduction No. Yards Adopting	Product Lifespan 5 years	10 years	15 years
4	161.04	328.48	495.92
7	288.86	584.13	879.40
4 ADJ	101.80	284.03	471.23
7 ADJ	182.60	505.07	835.61
Expansion	1.7937	1.7783	1.7733

Volatility	Volatility	Volatility	Mean
7.38%	10.25%	12.49%	10.04%
7.22%	10.11%	12.34%	9.89%
7.38%	10.25%	12.49%	10.04%
7.22%	10.11%	12.34%	9.89%

Finance Plan: $3.2m for 4 yards = $3.2m total

20% CT reduction No. Yards Adopting	Product Lifespan 5 years	10 years	15 years
4	192.29	387.79	583.28
7	341.16	685.53	1029.88
4 ADJ	121.55	335.31	554.24
7 ADJ	215.66	592.75	978.60
Expansion	1.7742	1.7678	1.7657

40% CT reduction No. Yards Adopting	Product Lifespan 5 years	10 years	15 years
4	182.93	369.07	555.21
7	341.16	652.77	980.75
4 ADJ	115.63	319.12	527.57
7 ADJ	215.66	564.42	931.92
Expansion	1.8650	1.7687	1.7664

60% CT reduction No. Yards Adopting	Product Lifespan 5 years	10 years	15 years
4	164.24	331.69	499.10
7	324.78	588.94	884.23
4 ADJ	103.82	286.80	474.25
7 ADJ	205.30	509.23	840.20
Expansion	1.9775	1.7756	1.7716

Volatility	Volatility	Volatility	Mean
7.25%	10.16%	12.42%	9.94%
2.57%	9.87%	12.14%	8.19%
7.25%	10.16%	12.42%	9.94%
2.57%	9.87%	12.14%	8.19%

Figure 6. Reduction in Total Ownership Costs

Figure 7 shows the input assumptions used in the strategic real options analysis, as well as Monte Caro risk simulation analysis for the two implementation strategies. Simulations of 10,000 to 100,000 trials were applied using these values, and the various combinatorial effects were collapsed into probability distributions and then simulated. The results were then used as inputs into the real options analysis. Figure 7 illustrates the two strategies' (Strategy A, phased implementation and Stragetgy B, rapid implementation) input into the real options model (e.g., the net reduction in total ownership costs minimum, most likely, and maximum values, implementation costs over time, simulated risk volatility and other assumptions).

Options Assumptions Used (Combined Analysis)

Strategy A: Phased Implementation

Asset (Distribution)	112.14 (Min)	312.32 (Likely)	517.87 (Max)	
Cost	$1.6M	$1.6M	$1.6M	$1.6M
Maturity	1 Year	2 Year	3 Year	4 Year
Risk-free	0.5%			
Volatility	41.65%			
Dividend	0%			
Steps	1000			
Expand Cost	$4.8M			
Economic Life	5 Years	10 Years	15 Years	
Probability	25%	50%	25%	
4 ADJ RAROC	$112.14	$312.32	$517.87	
7 ADJ RAROC	$200.70	$554.59	$917.23	
EF RAROC	1.7897	1.7757	1.7712	
Inflation	3%			
Inflation Adj. Cost	$1.60	$1.65	$1.70	$1.75

Strategy B: Rapid Implementation

Asset (Distribution)	114.16 (Min)	315.09 (Likely)	520.91 (Max)
Cost	$3.2M		
Maturity	4		
Risk-free	0.5%		
Volatility	41.07%		
Dividend	0%		
Steps	1000		
Expand Cost	$4.8M		
Economic Life	5 Years	10 Years	15 Years
Probability	25%	50%	25%
4 ADJ RAROC	$114.16	$315.09	$520.91
7 ADJ RAROC	$213.07	$557.71	$920.66
EF RAROC	1.8664	1.7700	1.7674

Figure 7. Real Options Valuation Input Assumptions

Figures 8 and 9 show the results from both strategies. Specifically, Strategy A's phased implementation (sequential compound option) shows a value of $546 million, whereas Strategy B has a value of $557 million. This shows that the rapid implementation has a higher strategic value in that, although the risk is slightly higher with the higher up-front investment amount, the saving received will be faster and the total invested cost is lower (as compared to the higher total investment cost for Strategy A). However, the values of the two strategies are quite close (within 2%). In addition Figure 9 shows that when simulation was applied to compare the relative values of Strategies A and B, Strategy B, the rapid implementation path, has a 53.20% probability of exceeding Strategy A. In fact, the relative risk measures show that both scenarios have very close relative risks (41.65% versus 41.07%). This further explains why the values of the two strategic real options are so close.

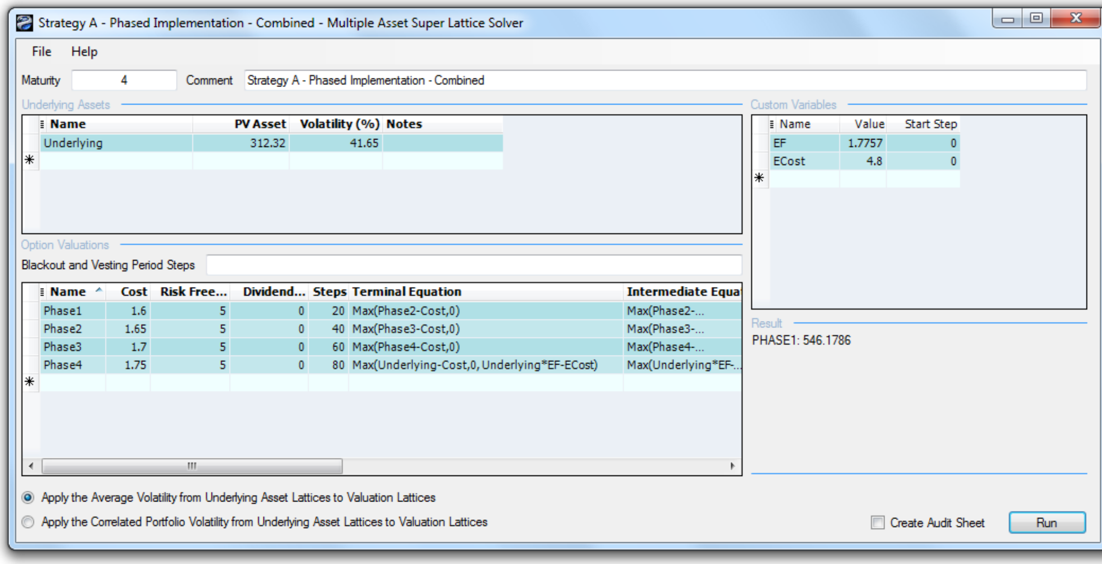

Figure 8. Strategy A's Real Options Valuation Results

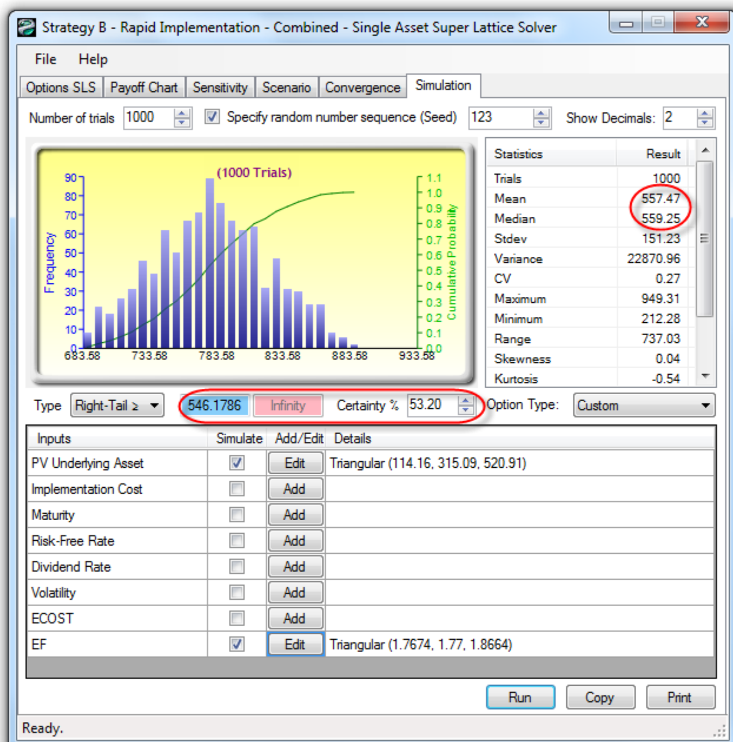

Figure 9. Strategy B's Real Options Valuation Results

The results of the simulations indicate that both Strategies A and B are valuable and that their values are very similar. This suggests that the choice of one strategy over the other should be up to the decision-maker based on which path makes more sense in an operational environment. Both strategies show a significant reduction in TOC overall, even after considering risk effects and diminishing marginal returns. An important aspect of generating these results is the assumption of diminishing marginal returns and the impacts of inflation. Figure 10 shows a single iteration of the diminishing marginal returns over time that was used, which incorporates a convex exponential utility function with inflation adjustments and diminishing marginal returns (this convex curve is similar to that shown in Figure A1's portfolio analysis investment efficient frontier in the appendix). The diminishing returns in this case reflect the reduced efficiency of resource use with additional investment. This diminishing factor or multiplier exists because the addition of shipyards will usually not return a linear increase or exponential increase. These factors were incorporated into the simulation model.

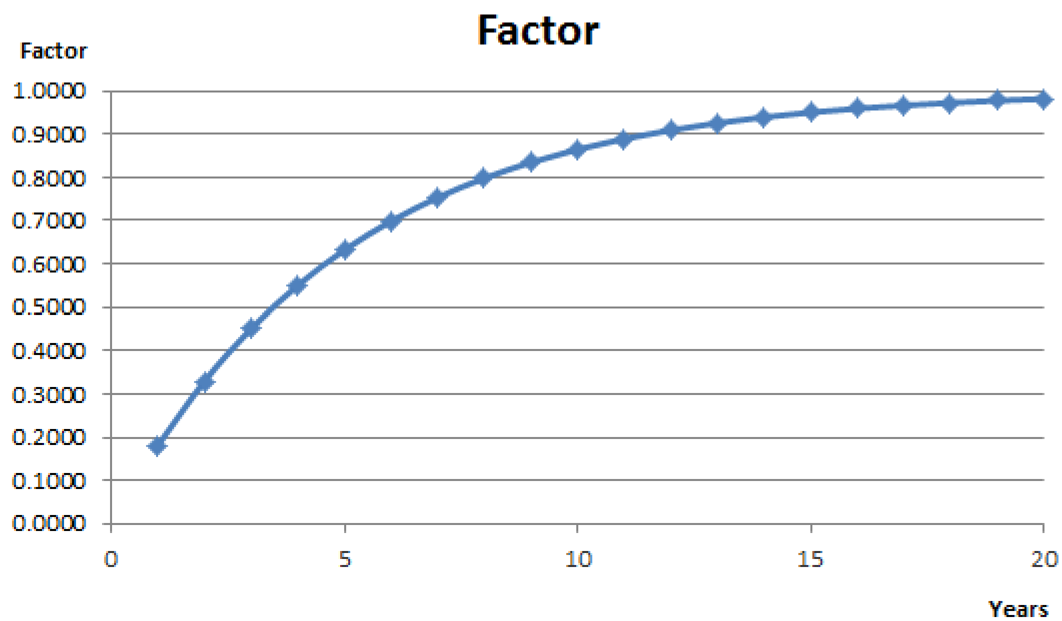

Figure 10. Risk-Adjustment and Diminishing Marginal Return Factors
(Time versus Diminishing Return Multiplier)

To understand how diminishing factors work, let's use a simple example. Suppose the savings on a single shipyard is $100M over its lifetime. Further suppose that the RTOC process can be implemented across several shipyards. The question now becomes, will implementing two shipyards save a total of $200M, three shipyards at $300M, and so forth? If this occurs, we have a linear return of $100M x N shipyards. However, according to microeconomic theory of diminishing returns and financial time value of money, we usually see a total return that is less than linear. The law of diminishing returns states that in all productive processes, adding one additional factor of production, while holding all others constant, will at some point yield lower per-unit returns—this does not imply that adding more of a factor will decrease the *total* production, which can occur, but we are referring to the fact that the marginal difference will decrease. For example, adding more workers to a job, such as the maintenance of a ship. At some point, adding more workers causes problems such as getting in each other's way, or workers frequently find themselves waiting for access to a part. In all of these processes, producing one more unit of output per unit of time will eventually cost increasingly more, due to inputs being used less and less effectively. Figure 10 illustrates an example profile of diminishing returns (which also accounts for time-value of money and inflation rates) over a 20-year period. For example, if there are 20 total shipyards, implemented one per year over the next 20 years, adding one additional shipyard causes a factor reduction of 0.1813, which means that the original savings of $100M for the base shipyard exists, and adding one more shipyard, instead of getting $200M in total savings, the total savings is reduced by this factor, or $100M + $100M(1-0.1813) = $181.9M. Similarly, adding 20 shipyards will reduce it by almost 1.00 (so the total savings is $2,000M instead of $2,100M). The figure is only illustrative and the curvature will depend on the rate of diminishing marginal returns, the timeline of adding shipyards, inflation and interest rates, productivity, and so forth.

Figure 11 shows the three possible reductions in TOC paths with the three product life spans across the various shipyards (the y-axis indicates one possible outcome of TOC reduction with respect to the number of shipyards implemented as shown on the x-axis). The conclusion is that this 3D TLS and collab-PLM project is highly valuable and beneficial to the DoD, as shown by the significant TOC reduction:

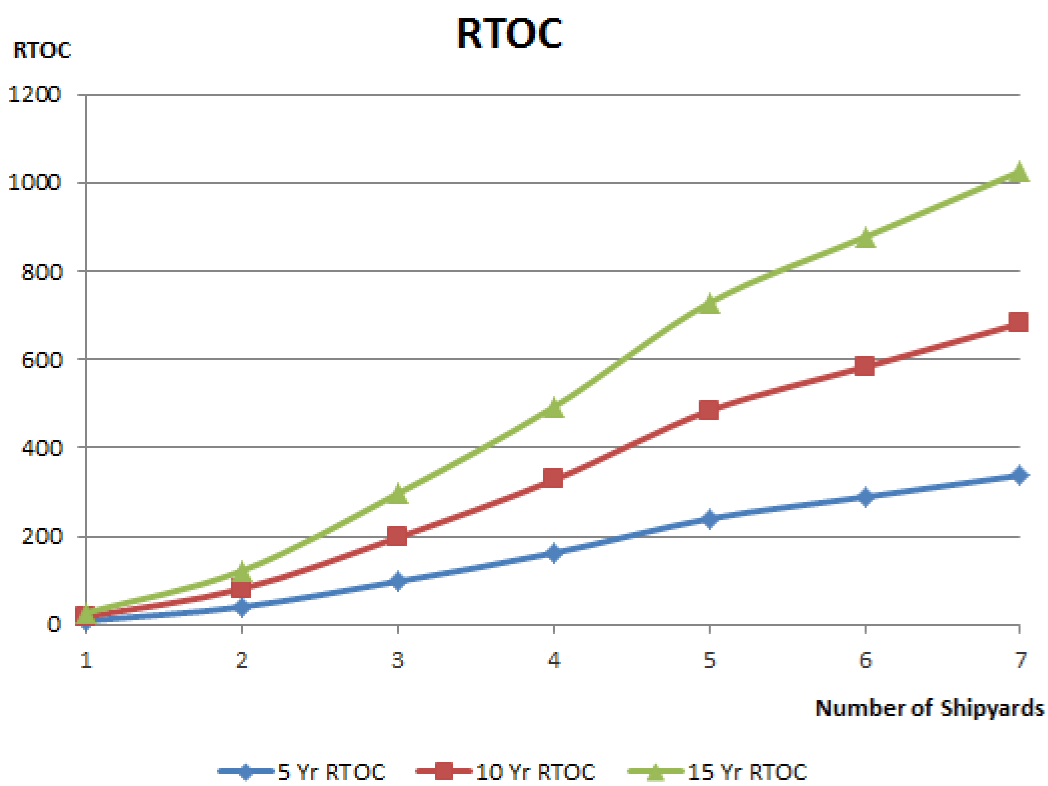

Figure 11. Reduction in Total Ownership Cost

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XIII. Discussion and Conclusions

The KVA+SD+IRM framework for modeling and evaluating DoD systems was applied to the adoption of collab-PLM 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 shipyard maintenance capacity. Simulations across a range of values for uncertain conditions describe a defensible range of potential savings. The KVA-SD modeling revealed and quantified an increase in shipyard capacity of 25% to 150% due to reductions in maintenance cycle-times. The results of the KVA-SD model were used in the IRM model to include uncertainties and strategic real options. Results indicate that both a phased implementation (Strategy A) and a rapid implementation (Strategy B) of collab-PLM and 3D TLS in SHIPMAIN processes are very valuable, generating a net total ownership cost savings of about $550 million compared to the current approach to ship maintenance.

A. 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 can be expected. In addition, 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 and, thereby, to better guide implementation. In addition to the cost savings potential, there is also the possibility of an increase in shipyard capacity for ship maintenance. If the fleet size grows to the level suggested by the Secretary of the Navy, it is entirely possible that this excess capacity will be consumed quickly. However, it also implies that the Navy will have greater flexibility in adding or reducing capacity using the two technologies. Such flexibility is critical in the coming budget-constrained DoD environment.

The results clearly point to the cost savings advantages of using collab-PLM + 3D TLS technologies. There appears to be no logical reason for delaying implementation of these two technologies based on the results of this study and the previous studies with similar cost savings projections.

B. 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. In addition, the current study identified and quantified the increase in shipyard capacity created by the adoption of the technologies and a potentially critical component of the Navy’s expansion strategy.

C. Limitations of the Current Study

The primary limitation of the current study is the absence of actual 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 provides 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. Future research must focus on obtaining historical ship maintenance process performance using the two technologies. Comparative analyses may also be possible with shipyards that have already adopted these technologies.

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Appendix. Integrated Risk Management and Portfolio Optimization

This appendix explains the basics of Modern Portfolio Theory (MPT) in general, as well as how it would be used in the next phase of this project, as it pertains specifically to 3D TLS and collab-PLM analysis.

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 nonsystematic risk and reward.

Portfolio optimization is an analytical technique for allocating scarce resources (limited budget, time, cost, and human resources) and meeting program requirements to satisfy and maximize strategic objectives, or, simply, for 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 the prioritization of those opportunities within resource constraints. 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 trade-offs of expected return on investment and risk. Using the Markowitz Efficient Frontier, 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, such as in analyzing 3D TLS and collab-PLM, 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. 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, requires that IT investments apply Return on Investment (ROI) measures. DoD Directive 8115.01 (DoD, 2005), 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 guidebook 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 The Chairman of the Joint Chiefs of Staff Instruction (CJCSI) 8410.01 (CJCS, 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 systems 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, it developed an approach that 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). It 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.

Future research will include 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 A1. 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, again referring to Figure A1, you would rather select Portfolio D than Portfolio E as the marginal increase is negative on the y-axis (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*

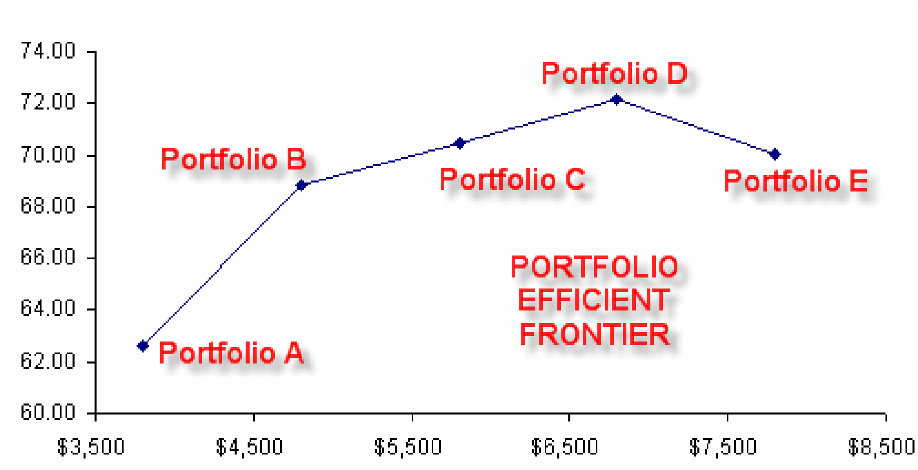

Figure A1: Efficient Frontier Example

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.

Appendix. Real Options Analysis

This appendix explains the basics of strategic real options analysis.

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

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

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

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

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).

Definitions of Variables

- *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 date for the underlying option

The preceding closed-form differential equation models 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):* $h_{i-1} = \frac{C_{up} - C_{down}}{S_{up} - S_{down}}$
- 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):* $q_i = \frac{S_{i-1} - S_{down}}{S_{up} - S_{down}}$

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 $q_i = \frac{S_{i-1} - S_{down}}{S_{up} - S_{down}}$.

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