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Quantitative Risk

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EXECUTIVE SUMMARY

The goals of this project are to develop, verify, validate, assess, and transition practical, relevant, and significant methods, procedures, and tools that provide objective and quantified indicators of acquisition program cost, schedule, and performance risk. The methods, procedures and tools are intended to complement, not replace, current risk management practices by providing early warning of risk exposure, i.e., of conditions that tend to increase the likelihood and/or severity of adverse acquisition outcomes. The primary products are (1) a set risk leading indicators, i.e., objective metrics calculated from standard program documents and contract data reporting items that provide early warning of areas of risk exposure, and (2) methods to calibrate and baseline the relationships between the risk leading indicators and program outcomes. Secondary products are (3) recommendations for Request for Proposal (RFP) language to improve visibility and transparency of risk exposure during Engineering and Manufacturing Development (EMD), and (4) recommendations for collecting and sharing data to calibrate/baseline risk estimating relationships across programs. The risk leading indicators point to root causes, and indicate the technical areas of risk in the program. The risk leading indicators address (1) evidence of risk exposure prior to EMD award, and (2) evidence of risk exposure during EMD execution. The risk leading indicators are intended for use by Government analysts and risk managers, and by EMD contractors in their risk management program. The risk leading indicators are being co-developed working with end-users, and are being validated and assessed by application to a major defense acquisition program, in concert with the program's Risk Manager. This report describes progress and results during 2014, focused on developing and verifying risk leading indicators, and plans for 2015, focusing on pilot application and evaluation in cooperation with a major defense acquisition program.

This research develops the concepts of risk exposure, risk leading indicators, and risk estimating relationships. The goal is to produce methods, procedures, and tools for risk early warning, source and cause diagnosis, to facilitate pre-emptive risk identification and mitigation. This approach complements traditional technical, cost and schedule risk management methods and stovepipes.

Risk exposure refers to conditions that amplify the likelihood and/or consequences of unanticipated complications, technical difficulties and delays. Exposure to risk increases the risk of adverse acquisition outcomes. Exposure to risk is created by overly optimistic goals that lead to inadequate margins for error, aggressive concurrent schedules counting on "things to come together at the end," deferred or limited testing, coordination shortcuts, adopting novel integration processes and promising but immature technologies. Unstable, inconsistent, incompletely resolved, and highly interdependent program plans and system engineering documents both indicate and create risk exposure. Lagging and uneven technical progress relative to the plan is a further indicator of risk exposure.

Risk leading indicators are objective metrics of risk exposure calculated from evidence in standard program management and system development reports and data. Risk leading indicators provide information to diagnose the areas and types of risk exposure, causes and effects. Risk leading indicators point back to root causes and forward to effects. There are many different potential sources of risk exposure, requiring different sources of evidence and calculations. The project is developing risk leading indicators that are (a) practical (i.e., can be computed from "standard" program management and system engineering documentation) and (b) relevant and significant (i.e., explain a large proportion and amount of variance between budgeted and actual outcome).

Risk estimating relationships are statistical, evidence-based, quantitative relationships to forecast the magnitude and uncertainty in program cost and schedule overrun, and performance shortfall from the risk leading indicators. Risk estimating relationships address the bias and uncertainty between actual and planned time, cost and performance of program activities, related to program maturation by technical area. Risk estimating relationships are similar to cost estimating relationships in traditional "analogy" models. Calibration must balance the sample set size and uniformity. Risk estimating relationships address both the bias and dispersion in time and cost estimation error, which makes calibration more sensitive to differences between programs than simple time and cost estimating relationships. Rather than attempt to forecast from disparate programs, we have developed methods to accumulate evidence from the individual program-of-interest to calibrate estimation bias and uncertainty. Risk of overrun is a function of the estimation bias and dispersion (uncertainty).

The approach is practical and relevant. It is tightly linked to standard deliverable data. It builds on the program risk evaluation frameworks and criteria set out, in formal documentation, for proposal and contact execution evaluation as determined by the PMO. It builds on prior empirical analyses of system development leading indicators, program risk leading indicators, and root causes and causal mechanisms of adverse acquisition outcomes.

This approach to acquisition program risk early warning complements traditional risk management practice and framework. The traditional risk management framework views a risk as a specific, identified potential future event, which has a known or estimated likelihood of occurrence and time/cost consequence if it occurs. Risk exposure addresses evidence of program conditions that elevate the potential for time and cost overruns, and technical performance deficiencies. Risk exposure analysis points to problem areas, for possible mitigation. Risk exposure analysis is not limited to "critical technology elements" but considers the entire program.

Risk exposure analysis complements and extends traditional cost and schedule risk analysis. Traditionally, risks in cost, schedule and technical progress in engineering and manufacturing development have been addressed in separate "stovepipes. Schedule risk analysis did not inform technical risk analysis, etc. Our approach to Risk exposure analysis using risk leading indicators and risk estimating relationships provides an integrated approach.

Significant developments are

(1) Specifying risk leading indicators related to root causes of adverse acquisition outcome and detectable in program documentation
(2) Producing a structure and method, within the context of standard acquisition documents and contract data reporting items, to provide integrated risk exposure analysis with pointers to technology/functional component areas, and to root causes
(3) Specifying a process to calibrate the expected impacts in the context of the specific program under consideration.

Further research and development plans are to demonstrate, test and evaluate the risk leading indicators and risk exposure calibration methods to assess practicality, feasibility, relevance and significance via application to acquisition programs pre- and post-EMD award.

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INTRODUCTION

The project goal is to develop, verify, validate, assess, and transition practical, relevant, and significant methods, procedures, and tools (MPT) that provide objective and quantified leading indicators of acquisition program cost, schedule, and performance risks. The methods, procedures and tools are intended to complement, not replace, current risk management practices by providing early warning of risk exposure, i.e., conditions that tend to increase the likelihood and/or severity of adverse acquisition outcomes. The primary products are (1) a set risk leading indicators (RLI), i.e., objective metrics calculated from standard program documents and contract data reporting items that provide early warning of areas of risk exposure, and (2) methods to calibrate and baseline the relationships between the risk leading indicators and program outcomes. Secondary products are (3) recommendations for Request for Proposal (RFP) language to improve visibility and transparency of risk exposure during Engineering and Manufacturing Development (EMD), and (4) recommendations for collecting and sharing data to calibrate/baseline risk estimating relationships across programs. The risk leading indicators point to root causes, and indicate the technical areas of risk in the program. The risk leading indicators address (1) evidence of risk exposure prior to EMD award, and (2) evidence of risk exposure during EMD execution. The risk leading indicators are intended to be used by Government analysts and risk managers, and by EMD contractors in their risk management program. The risk leading indicators are being co-developed working with end-users, and are being validated and assessed by application to a major defense acquisition program, in concert with the program Risk Manager. This report describes progress and results during 2014, focused on developing and verifying risk leading indicators, and plans for 2015, focusing on pilot application and evaluation in cooperation with a ground combat major defense acquisition program (MDAP).

The steps of the technical approach are

(1) To develop provisional RLI by building on prior NDAI/INCOSE work on system development leading indicators, GAO "best practices", and prior research by IDA, MITRE and others on root causes of adverse acquisition outcomes and their causal mechanisms

(2) To derive RLI from the requirements and evaluation criteria in RFP packages in order to ensure that the RLI that reflect concerns and evidence of program progress from the perspective of the program management organization

(3) To cross-reference the RLI to program documents and contract reporting data items, in order to ensure that the data are will be available to calculate the risk leading indicators

(4) To verify the suitability and credibility of the RLI by co-developing them with end-users, specifically the TARDEC Risk Management Group, and by periodic technical exchange meetings with other end-users (e.g., the US Army Materiel Systems Analysis Agency, AMSAA), theoreticians at RAND, MITRE, IDA, and academics, and discussions with DASD personnel

(5) To develop methods to calibrate the RLI (a) to any specific program using contract reporting data on program cost, schedule and performance progress, and (b) across programs using such reporting data as are archived and shareable across programs

(6) To validate and evaluate the RLI by pilot application to a major defense acquisition program, working in coordination with the program Risk Manager and the TARDEC Risk Management team

(7) To facilitate transitioning the methods, procedures and tools to the end-user community by working with them to develop and pilot the methods.

Activities in 2014 focused on steps 1-4, developing provisional RLI. The primary focus for 2015 will be on steps 5-7, piloting the RLI. In 2014, we reached an agreement with a MDAP to pilot the RLI in support of program risk management, in a collaboration between SERC researchers, the TARDEC risk management team, and the program risk manager. However, the program was in source selection for the EMD phase until late December 2015. During this time there was turnover in the PMO. We decided that we needed to reaffirm the collaboration agreement and had a joint meeting in February 2015 to re-connect. In February 2015 we initiated discussions with another ground combat program ("Future Tank") that is earlier in the acquisition life-cycle to pilot pre-EMD RLI.

The pilot applications to demonstrate the value of the RLI and facilitate transition into use are the primary focus for 2015. We also plan to pursue, at a low level of effort, RLI specifically formulated for software-intensive cyber-physical systems with real-time, distributed, embedded processing integrated with sensors and actuator electronics.

2014 OBJECTIVES, SCOPE, APPROACH, FINDINGS AND RESULTS

OBJECTIVES AND SCOPE

The primary 2014 objectives were to develop practical, relevant, and significant leading indicators of risk exposure, i.e., program conditions that amplify the likelihood and/or consequences of unforeseen future events and interactions, and of normal variances in activity time, cost and performance. Adverse consequences include development time and cost overrun, technical performance and reliability shortfall, and excessive production, operation, and sustainment costs. Risk exposure is the result of unrecognized or unacknowledged past events, decisions and actions, and current uncertainty, inconsistency, incompleteness, and interdependency in the system development.

Risk exposure early warning refers to detecting evidence of the root causes and effects before there are significant adverse consequences. Its purpose is to alert program management to areas of elevated risk exposure in the program. Risk exposure early warning combines program cost, schedule and performance data in an integrated view.

Risk exposure early warning complements the risk identification practices and procedures in the DoD Risk Management Guide [1]. The intent of the Guide is "*to help ensure program cost, schedule, and performance objectives are achieved at every stage in the life cycle*" and to present processes "*for uncovering, determining the scope of, and managing program uncertainties.*"

The Risk Management Guide defines a risk as a potential future event which, if it occurs, would have adverse consequences, for which the probability that it will occur and the consequences, if it occurs, can be assessed. Risks with high combined likelihood and magnitude are priorities for tracking and mitigation. The practices and procedures in the guide start with identifying risk events. Risk exposure early warning does not itself identify causes or mitigations. It detects conditions of elevated exposure to risk and it points to evidence to help orient risk and issue management investigation.

The procedures and practices in the Guide rely on Subject Matter Experts (SMEs) to identify and quantify risk events. Risk exposure early warning provides an evidence-based analytic approach that complements SME insight. The Air Force Cost Risk Handbook [2] identifies common factors leading to bias and dispersion in SME estimates of time, cost, technical performance, and of identification and estimation of likelihood and consequences of risk events. It lists eight motivational factors (management pressure, social pressure, group think, wishful thinking, career goals, misunderstanding, project advocacy, and competitive pressures) and five cognitive bias factors (inconsistency over time, anchoring, irrelevant analogies, underestimation, and human nature).

Risk exposure early warning is based on understanding the causal chains from root causes to adverse outcomes, and how the effects manifest in standard program and system development data and reports. Risk exposure early warning has two major components: Risk Leading Indicators (RLI), and Risk Estimating Relationships (RER).

RLI are computed from standard program documentation and contract data reporting items (CDRI). RLI compare data across different reporting requirements and over time to measure incompleteness and inconsistency, instability, uneven or inadequate progress, and interdependency of the program and system organization. The RLI are evidence of both (1) root cause problems with potential for persistent future effects, and (2) conditions that increase the potential for, and/or sensitivity to, unforeseen future events and execution-versus-plan variances. The RLI were developed through examination of risk considerations in proposal evaluation and program execution criteria and reporting, published root cause analyses, best practices metrics for schedule risk analysis, and published research on system development leading indicators.

Risk Estimating Relationships (RER) are statistical models that use the RLI to estimate future bias and uncertainty in program activities time, cost and technical performance. The RER are calibrated to data from completed Integrated Master Schedule (IMS) activities of the current program, and are updated over time. Each completed activity in the IMS provides a data point. RER can be as simple as thresholds for "high" and "low" risk exposure, or as complex as regression models to forecast the likelihood and expected magnitude of cost and schedule overrun, or system performance shortfall. System performance shortfall is evidenced by capabilities deferred to future product improvements, and/or reduced capability goals.

The research is organized into two parts based on the DoD acquisition lifecycle: (1) pre-EMD award, and (2) post-EMD award. Prior to EMD award, the Government has the authority and responsibility to define the parameters of the EMD program. After EMD award, the Government's role is largely one of monitoring and evaluation, leading up to the Milestone C decision whether or not to proceed to production. Up to the point of EMD contract award, the Government frames the acquisition program in terms of the system performance and cost, and the EMD time and cost. After EMD contract award, the Government and contractor are bound by the terms of the award, subject to negotiated changes. From the system acquisition perspective, there are risks embedded in the program prior to EMD award, and other risks in the EMD execution.

The scope of this project excludes risks of Congressional decisions (funding of the program of interest, and competing programs/plans; cost impacts of location of R&D and production, etc.). The scope excludes risks of long time to fielding and slow rate of production. These are Government decisions driven by considerations outside the scope of program time/cost/risk capability.

APPROACH

We began by reviewing prior research pertinent to developing RLI. We reviewed prior analyses of root causes of adverse program outcome. We identified Program Management Office (PMO) risk issues and perspectives expressed and implied in the evaluation criteria and reporting requirements in Request for Proposal (RFP) packages over several ground vehicle programs. We reviewed reports on system development leading indicators. We reviewed metrics from recommended procedures and "best practices" for program, cost and schedule management.

We then compared the potential indicators and metrics to sources of data and evidence in program management and systems engineering baseline and update reports, and contractor data reporting items. We then defined an initial set of evidence-based risk leading indicators that

(1) can be computed from computable from data in typical program management and systems engineering reports and updates

(2) address significant root causes of adverse acquisition outcome

(3) indicate the technical areas of the program contributing significantly to the risk exposure for risk management review and mitigation.

We examined issues in using data from previous programs to calibrate cost estimating relationships as a proxy for risk estimating relationships. We examined the availability and accessibility of data from past programs to use to calibrate risk estimating relationships. We concluded that access to relevant calibration data from past programs would, in many cases, be difficult if not impossible. Therefore we developed the outline of a method to use current program data to self-calibrate the risk estimating relationships to predict the probability and magnitude of time and cost overrun.

PRIOR RESEARCH FOUNDATIONS

ROOT CAUSE ANALYSES

The Government Accountability Office (GAO) [3] reported that in fiscal year 2012, of the 85 major defense acquisition programs under review, 39 percent had unit cost growth of 25 percent or more, the average delay in initial operating capability was 27 months, the average change in development cost from the initial estimate was 49 percent, and the average change in total acquisition cost from the initial estimate was 38 percent. The report finds that programs experiencing cost and schedule growth "*share a common dynamic: moving forward with programs before the knowledge needed to make decisions is sufficient*." The report identifies seven common root causes: (1) concurrent testing and production, (2) optimistic assumptions, (3) delayed testing, (4) insufficient tradeoffs among cost, schedule, and technical performance requirements during early planning, (5) unrealistic cost and schedule estimates, (6) Insufficient testing during development, (7) insufficient attention to reliability.

The GAO [4] identified 12 root causes: unstable program requirements, funding and quantities; complex systems; diminishing industrial base; new processes; immature or cutting edge technologies; first time integration; unrealistic assumptions and projections; overoptimistic program baselines; inexperienced staff; lack of relevant historical data; unreliable Earned Value Management (EVM) data; and inadequate contingency schedule slack and management reserve funds.

The Office of Performance Assessments and Root Cause Analyses (PARCA) [5] found five root causes of adverse acquisition outcomes attributable to planning and execution: (1) unrealistic cost or schedule estimates, (2) immature technology with excessive manufacturing and integration risk, (3) unrealistic performance expectations, (4) unanticipated design, engineering, manufacturing or technology issues, and (5) poor management performance. Poor management performance included ambiguities combining requirements and requirements documents, interface management, tradeoffs within holistic performance attributes (size, weight, power, cooling, etc.), and risk assessment.

In 2008, the NDIA Systems Engineering Division in conjunction with DASD-ATL-SE produced a report on the systemic root causes of program failures [6] concluding that "*the most significant causes were directly related to poor or inadequate activities early in acquisition strategizing and planning efforts and in conducting management gate reviews during the early stages of execution. Lastly, the analysis also concluded that there was a significant root cause related to staff size, training and experience*."

The Defense-Industrial Initiatives Group at the Center for Strategic & International Studies [7] found that of 85 major programs, overoptimistic estimates were the primary driver for cost growth and changes in quantity were the second leading cause. A RAND study [8] found that in their analysis of 35 programs, changes in quantity accounted for more than half of cost growth, and that "*decisions to change the schedule, additional requirements, and cost-estimating errors account for almost all of the remaining procurement cost growth*." The Institute for Defense Analysis [9] found that "*Virtually every program we surveyed experienced cost problems that could have been avoided or ameliorated through better front-end analysis of overall design issues and risks. Serious attention to system-level risk seems to have been lacking on the part of senior decision makers*."

In summary, root causes include: unstable requirements; incomplete or unstable planning; overoptimistic or inaccurate estimating; underappreciated or misunderstood technical and engineering challenges; deferred or insufficient verification and testing during development; unforeseen interactions and interdependencies in the system requirements, architecture and design; deferred tradeoff decisions; unforeseen interactions and interdependencies in the execution task schedule or organization; lack of "margin for error" in budget, schedule, performance and design; data quality and availability of relevant historical data.

PROPOSAL EVALUATION AND CONTRACT MANAGEMENT

Fair, equal and open competition guidelines require that RFP packages clearly state (1) what information to provide in the proposal (section L), (2) how the proposals will be evaluated (section M), (3) the Scope of Work (section C), and the Contract Deliverable Requirements List (CDRL; typically Appendix A). The RFP package typically includes attachments that specify documentation frameworks and criteria. The CDRL section specifies requirements for reports and updates on periodic or event-based timelines, and the required format and content. Baselines are required either with the proposal, or at a specific subsequent technical review event. The RFP package typically includes guidance for duration of TD and EMD phases, funds available for each phase, number of EMD prototypes, number of Low Rate Initial Production units, etc. The RFP package also includes targets for performance (requirements) and constraints.

Section M specifies how the Government will evaluate the risk-vs-reward to reject unsuitable bids, and to select from among suitable bids. Risks are the risks of failing to deliver prototypes that will pass Operational Testing (per specified failure definitions and scoring criteria) for performance and reliability on schedule and within development budget, of failing to be ready for Low Rate Initial Production (LRIP) at the end of the EMD, of failing to meet LRIP unit cost targets, and/or failing to be able to meet fuel economy, reliability and logistics support goals. Rewards are the proposed time, costs, and system performance. Risk-reward tradeoffs are considered both in proposal evaluation and in program management decisions to trade lower performance for lower cost-schedule risk, for increased design tradespace, and/or for increased reliability.

The level of risk in the proposed program is judged based on the claimed level of design, manufacturing, production cost, and RAM maturity, considering the thoroughness and credibility of the supporting data. Maturity levels are clearly defined with specific completion criteria based on systems engineering, design, integration, analysis, manufacturing, and testing artifacts. The specific criteria for maturity levels combine essential technical performance measures, systems engineering and design technical review knowledge points, and verification results. The highest levels of maturity correspond to completion of the contract requirements with tests completed on manufactured systems, with substantiating cost data and correct action plans for any deficiencies.

Maturity level advancements are progress accomplishments on the path to successful program completion. Using maturity levels to track technical progress is a well-defined and is consistent with the PMO framework for program risk assessment. Maturity level advancement vice the program plan is a potential indicator of risk. Maturity level advancement, over the entire program and by WBS element, can be integrated into the scheduling and reporting framework simply by including maturity advancement in the IMP, so that IMP events, accomplishments and criteria include maturity advancement of the design, manufacturing, and RAM. Making maturity advancement events part of the IMP forces cost and schedule reporting to be reported relative to demonstrated maturity. Maturity levels are organized by stages of system acquisition: development, production, and operation & sustainment. Maturity level assessments take a life cycle cost and capability view. Technology, integration, and manufacturing readiness views and consistent perspectives, focused on TD and EMD acquisition stages.

The RFP package includes additional requirements for risk assessment in proposal evaluation and contract execution. Executing a risk management plan, per the DoD Risk Management Guide, is required to identify and address potential future events with significant likelihood of occurrence and significant consequences if they do. Technology Readiness Assessment (TRA) [10] is required for those technologies designated as Critical Technology Elements (CTE) and Other Technologies of Interest (OTI). TRA involves detailed, engineering-level analysis by Subject Matter Experts. It is focused on the development of selected technologies and subsystems, not the entire development program. Integration Readiness Assessment (IRL) and Manufacturing Readiness Assessment (MRL) are not always required.

Technical review checklists contain over 800 specific questions in 13 categories to gauge progress at each of the major program reviews. Progress for each question is scored red, amber, green, unknown, or not applicable. A team at RAND has proposed using the technical review checklists as the basis for risk assessment [11]. The categories are review entry readiness, planning, schedule, management, staffing, process, product support, requirements management, system design, system verification, program risk assessment, certification and legal, and review completion.

Schedule risk assessment, e.g., using the Defense Contract Management Agency (DCMA) 14-point schedule assessment, GAO schedule assessment or similar approach, is typically required. Methods for schedule risk assessment, and the understanding of critical paths, near-critical paths and high schedule risk activities in non-deterministic programs, are evolving.

The RFP package specifies the program management and system engineering baselines and update reports, including content, format, and frequency or event timing. These provide the basis to evaluate risk leading indicators and to calibrate risk estimating relationships.

SYSTEM DEVELOPMENT LEADING INDICATORS

The NDIA System Engineering Division [12] found that "*Technical decision makers do not have the right information & insight at the right time to support informed & proactive decision making or may not act on all the technical information available to ensure effective & efficient program planning, management & execution*". The NDIA formed a working group to develop a set of system development leading indicators to provide insight into technical performance at major decision points for managing programs quantitatively across their life cycle, with emphasis on TD and EMD phases, and objective measures of commonly and readily available data.

The NDIA project used surveys to identify high-value areas for system development leading indicators, building on prior work on systems engineering leading indicators [13]. The system development leading indicator categories [14, 15] were:

1. Requirements Stability
2. Proportion of Stakeholder Needs Met and Verified
3. Interface Completion Trends
4. Staffing Skills and Trend
5. Risk Burndown
6. Technical Performance Measure (TPM) Trends
7. Technology Readiness Level
8. Manufacturing Readiness Level
9. Architecture
10. Affordability
11. Requirements Verification
12. Defects and Errors

Specific leading indicators were defined in some of the categories. The indicators were not directly tied to specific contract data requirements. Typical contract data requirements relate to categories #1, 2, 5, 7, 8, 9, 10 & 11. Proposal evaluation and contract management criteria suggest additional indicators, supported by specific technical status and progress reporting, and directly related to program risk considerations in program decisions.

The NDIA survey referenced Kohl and Carson [16] reporting on a Practical Software & System Measurement workshop on architecture measurement concepts. Although the workshop focused on software and system architecture, the concept of architecture also applies to the program architecture as expressed in the IMS, to the requirements architecture, and other knowledge structures in program management and systems engineering. The workshop consensus identified six dimensions of architecture development for measurement: size, interconnectedness, completeness, compliance, consistency, and cost. "Stability" was not included. Sources of input data and methods to calculate measures from the data were not specified.

The Defense Contract Management Agency (DCMA) approach to technical performance risk assessment evaluates variances of technical progress versus cost and schedule to indicate the level of risk and detect new risks before their effects on cost/schedule are irrevocable [17, 18]. Technical progress is measured by the Technical Performance Measures (TPM) for the Technical Performance Parameters (TPP). Cost and schedule are measured with the Earned Value Management (EVM) system. The TPP and TPM are formulated for the particular program, and are derived from the major system performance parameters. In this model, TPM progress against the plan is the basis for leading indicators of risk.

Best Practices for Schedule Risk Assessment

The GAO schedule risk assessment guide [19] addresses measurement of schedule health with quantitative approaches to analyze the completeness, consistency, interdependency, safety margins in a program schedule. The metrics include: the number and proportion of "long" activities; ratio of activities to dependency links in total and by each of the four types of logical dependency; ratio of detailed activities to milestones; number and proportion of activities no mapped to a milestone or Integrated Master Plan (IMP) event; number and proportion of activities with many predecessor links, with many successor links, with no successor, and with no predecessor; critical path float to each milestone; and number of activities with negative or low float relative to their planned duration. The guide also includes of schedule execution, e.g., number of activities that were started or finished before their logical dependency condition, number of activities that started or finished late, mean and standard deviation of the difference between actual and planned duration, start date, and end date.

The GAO Guide recommends using probabilistic schedule risk analysis to complement deterministic critical path analysis. Probabilistic risk analysis requires data on the distribution of activity duration, e.g. the minimum, most likely, and maximum, and data on the correlations between activity durations. Simulation is used to compute the probability distribution of total time. The probability the program will be late or milestone missed, and the expected amount late given it is late, are computed from the distribution. However, no published data has been found showing that people can reliably estimate the distribution of activity durations or the correlations between activities. A detailed IMS can have upwards of 5,000 activities, and providing probability distribution and correlation estimates can be onerous. Probabilistic risk analysis does not directly identify which activities are putting the schedule most at risk. Further development and verification of practical methods for schedule risk analysis are needed.

Statistical Estimating Relationships

The concept of RERs was inspired by the statistical approach to Cost Estimating Relationships (CERs). CERs estimate cost by calibrating a model of historical cost data as a function of a set of explanatory factors [2, 20, 21]. The proportion of cost variance explained by a CER is a measure of the accuracy of the model. Open questions in developing CERs include: choosing the population of "similar" cases to pool together; choosing the explanatory factors; choosing the general analytic model type. These choices are interrelated. Larger pools of more diverse programs may provide more or less consistent evidence of different interactions and dependencies. When the ratio of data points to explanatory variables and model parameters is low, there is a risk of spurious correlation. Some explanatory variables may be highly correlated, or correlated in some programs but not others. Data from the program of interest may be sparse, but is highly relevant.

The significant issues in formulating CERs are (1) choice of the systems to pool as a population of similar cases, balancing population size and diversity, (2) choice of the explanatory factors, i.e., independent variables, (3) choice of the underlying regression technique. Of these three issues, the first two are the most important. In practice, limitations in data quality and quantity limit CER accuracy, more than differences between regression techniques.

Pooling over a diverse population attenuates and obscures the effects of individual factors and interaction effects. A small population risks biases from small sample size. Pooling multiple programs is needed to reduce statistical uncertainty, but overbroad pooling increases uncertainty [22].

CERs estimate cost. The regression for CER calibration produces an estimate of the accuracy of the model, i.e., the proportion of variance in the sample data explained by the model and the expected error in the model predictions. But CERs do not attempt to estimate the dispersion in cost as a function of the input variables. They estimate cost, but not cost variability.

RERs are an analog to CERs, but with the addition of estimating variability as well as expectation. Unexpected adverse outcomes result from *bias* in the program estimates of time, cost and performance and uncertainty (also called *dispersion*) in the difference between estimates and actuals. RERs explain the accuracy of time/cost/performance planned versus actual outcomes. Accuracy has two components: (a) bias or offset, and (b) random dispersion or uncertainty.

Risk sources may differ from program to program, from acquisition stage to stage, and between WBS elements. Sources of risk exposure can be highly varied between different individual programs of the same type due to a wide variety of factors including marketing strategy, experience of the engineering and engineering management team, aggressiveness of the cost, schedule and performance goals, technology, engineering, and integration challenges, etc. Different program can have different reporting requirements and interpretations. Above and beyond the difficulty of sharing data across programs, the diversity of programs is a major obstacle to calibrating RERs to past program data.

An alternative is to calibrate the RERs to data from the individual program. This ensures relevance. The limitation is that at the start of the program, there is no data. As the program proceeds and data are collected, the RERs can be calibrated. To obtain statistically valid samples, calibration data points should be at the lowest level of the IMS with time and cost reporting – each completed IMS activity is data point, conditioned on being part of the same program.

FINDINGS AND RESULTS

CAUSAL MECHANISMS

This section presents a synthesis of the published analyses on root causes, acquisition, program and contract management, and system development, augmented by first-hand experience on acquisition program execution and Independent Review Teams. The observations in this section are the rationale for the choices of risk leading indicators and the integrated risk early warning approach.

<u>Optimistic Estimates Have Real Consequences</u>. "Success oriented" program plans create skewed distributions with long tails: appealing planned results, but with greater adverse consequences when problems occur. In an effort to "sell" a program and/or to win a bid, senior management can be tempted to make optimistic claims for time, cost, technical performance, reliability, and potential risks. Since adverse acquisition outcomes are deficiencies relative to how the program was sold, optimistic claims increase risk by reducing the margin for error and uncertainty.

Beyond this “statistical” effect, optimistic estimates have real effects on the program plans that lead to elevated risk exposure. An optimistic timeline leads to aggressive schedule structures. Characteristics of an aggressive schedule structure include: concurrent (parallel but independent) paths that come together towards the end; limited incremental integration analysis, verification and testing; low schedule slack margin for error; and time estimates that are more optimistic for activities later in the schedule. Programs concurrent paths and limited intermediate integration and verification (“it all comes together at the end”) do not produce the information to detect and correct problems until it is too late. Aggressive cost goals lead to reduced and deferred developmental analysis and testing, and to eliminating parallel execution of alternative backup approaches. Aggressive performance goals lead to adopting less mature advanced technologies that are more likely to have unforeseen integration issues. Aggressive schedules lead mid-level managers and engineers to take shortcuts. Over optimistic goals have real effects that elevate exposure to risk.

<u>Allowing Margin For Error Reduces Risk Exposure</u>. Limited margin for error creates exposure to risk. When there is little or no safety margin, small unforeseen events and “natural” variances due to uncertainty can have amplified effects. When there is more safety margin, larger impacts are needed to produce adverse consequences. Schedule margin (also called slack or float) covers schedule slip are rework time. Cost margin (management reserve) covers unforeseen costs and gives management flexibility. Performance margin provides tolerance for unforeseen interactions that could degrade overall capability. Design margins for holistic system properties such as size, power, weight, cost, reliability, etc. provide tolerance for unforeseen growth in burdens. The GAO recognized the need for management reserve and schedule slack. Tradeoffs between performance levels and holistic burdens are recognized in program management and systems engineering. Contract award practices to recognize margins and uncertainty in cost, schedule and performance are evolving.

<u>Past Performance Predicts Future Performance</u>. The root causes of time and cost overruns and technical accomplishment shortfalls in IMS activities do not go away by themselves. If the planning was overoptimistic, if technical challenges were not well-understood, if the executing organization has internal problems, etc., and if there has been no underlying change, then the root causes and dynamics will still be at work, and similar patterns of bias and dispersion in the outcomes of completed activities relative to the plan are likely to show up in the future. In this situation lagging indicators become leading indicators.

<u>Potential Risks Are Everywhere And Entangled</u>. Every requirement that has not been verified, every schedule activity that has not been completed, every architecture element that has not been designed, integrated, and tested expose the program to risk. Decisions affecting uncertainty and accomplishment in one acquisition phase have impacts on other phases. Decisions that affect uncertainty and accomplishment in cost, schedule and technical performance are interrelated. Decisions and tradeoffs in one WBS or IMP element can have impacts on others. Lacking a model and data on these interactions creates ignorance that exposes the program to risk.

<u>Evidence Reveals Risk Exposure</u>. Program reports - baselines and updates of system development data, linked to program execution data – are useful to detect and diagnose risk exposure when they are timely, with sufficiently complete, consistent, and accurate content. Reporting and analysis of evidence has costs that must be considered relative to benefits, just as incremental integration and verification has costs and benefits. Risk early warning can leverage standard reports and work within the framework of standard contract data requirements. The standard reports and reporting schedules have been developed to inform particular program stage gates and PMO decisions, but were not specifically designed for integrated risk early warning. Integrate risk early warning could benefit from (1) update scheduling for proactive choices vice reactive assessments; and (2) standardized content, format, and

terms across different artifacts to help ensure consistency and completeness. Standardized language for RFP packages is the mechanism for implementation. Contractors will benefit from standardized contract language by knowing what data content, information, and terms to provide, and how the data will be assessed. Increasing transparency to the offerors improves the quality of responses, and the ability to compare competitor responses. Objective data reporting and clear evaluation criteria are essential for open and equal competition among vendors

<u>The Program Manager's Office (PMO) Establishes the Risk Tradeoff Terms and Conditions</u>. The PMO is the definitive source for understanding priorities and tradeoffs among EMD cost, schedule, technical performance & reliability, production and O&S cost and risks of not meeting claims. The PMO determines the evaluation basis and criteria to compare the risk and reward of alternative proposals. The PMO specifies the priority levels for different performance parameters and constraints. The PMO decides how to trade off development time and cost versus initial performance and reliability versus production cost versus reliability growth and performance upgrade though continuous modernization versus operation and sustainment cost and logistics footprint. Risk exposure assessment must be consistent with the PMO value proposition to be relevant. The same risk priorities and considerations apply after contract award as during proposal evaluation, albeit with additional data. Risk exposure early warning must be informed by and consistent with the proposal evaluation criteria and the contract reporting/management criteria in the RFP package produced by the PMO.

<u>Buried Tradeoffs & Constraints Indicate and Cause Risk Exposure</u>. Sometimes programs have constraints and/or tradeoff relationships between one factor and another that have not been included in the product specification, e.g., size, power, weight, production cost, operational reliability and maintainability, continuous modernization capacity, etc. Sometimes increasing performance on one parameter can compensate for, or allow margin for, another. Decreasing performance goals in one area can increase the design constraint tradespace over the entire system. Increasing clarity of the constraints & tradeoffs reduces risk of offerors going "off in the wrong direction."

<u>Instability Indicates and Causes Risk Exposure</u>. Unstable requirements, plans, and architectures create re-work and wasted effort, and uncertain outcome. Instability can be evidence of inadequate planning and understanding the technical content, implying continued future instability. Changes create re-work, and indicate past planning deficiencies that will, if not corrected, lead to future incompatibilities and re-work.

<u>Interdependency and Incompletely Resolved Elements Indicate and Cause Risk Exposure</u>. Requirements, system architectures, and program schedules are all networks of interconnected nodes. Larger and more highly interdependent networks have more opportunities for unforeseen interactions, frictions, and ripple effects. There are more opportunities for adverse interactions if a new node or link is added. When nodes that are not fully resolved (e.g., a planning package in the schedule versus defined task, a requirement that has not been decomposed and linked, or an architecture element does not have completed boundary diagrams) are eventually resolved, there are more opportunities for adverse interactions in more complex networks. Unresolved elements are evidence of incomplete planning and/or understanding the system and/or program. Unresolved elements add uncertainty into estimates, and may have hidden dependencies. Unresolved elements can hide development obstacles and difficulties, and thus leading to overoptimistic estimates. The GAO recommends that no detailed activity be longer than 44 days, recognizing that long activities are evidence of incomplete resolution and that longer activities tend to have greater uncertainty. The GAO also recommends analyzing IMS network characteristics to assess schedule risk. Similar, though not identical, methods can apply to the requirements network, the system architecture, and even to the interconnected network of the requirements, IMP/IMS, and system architecture.

Compliance Verification and Developmental Testing Buy Down Risk. Less verification, incremental integration and testing during development creates more opportunity for unhappy surprises at the end of the program when time and funds for corrective actions are constrained. Earlier verification provides more time margin for corrective action. Verification and developmental testing require commitment of time and funding. Different means of verification include design inspection and engineering judgment, modeling and simulation, isolated bench testing, partially integrated testing, and fully integrated testing.

Technical Progress Needs Visibility. Reporting to reveal real technical progress is needed to assess risk. Without evidence, early warning is unfounded. Objective measures, e.g., development, production and RAM maturity by WBS element, provide diagnostics. Slower than expected technical progress indicates initial planning bias. Uneven technical progress indicates planning inaccuracy or underappreciated difficulty. Incomplete, inconsistent, missing or “to be determined” fields in program management and system engineering baselines and reports are is evidence of uncertainty, which could lead to new tasks, longer times, more coordination, etc.

Different Programs are Different. Different programs have different engineering and manufacturing challenges, different contractors, different engineering management practices, and different levels of skill and experience. Different programs will have different sources of risk. These differences make it difficult to extrapolate from one program to another. Risk Leading Indicators that were relevant to one program may not be relevant to another. Quantitative relationships between leading indicators and outcomes on one program may not be accurate for another program. Aggregating across disparate programs would dilute and obscure the significant relationships, as seen in empirical studies of Cost Estimating Relationships (CER) across different domains [22].

PROPOSAL AND CONTRACT DATA FOR RLI

Risk early warning employs baselines and updates for seven standard data reporting elements. Three are program management products: the Work Breakdown Structure (WBS), the Integrated Master Plan (IMP), and the Integrated Master Schedule (IMS). Five are systems engineering artifacts: the System Segment Specification (SSS), the Specification Tree (ST), the System Architecture (SA), Technical Review Checklists (TRC), and the Manufacturing Cost Estimate (MCE). The RFP package specifies the content, format, preparation instructions, initial delivery and update schedules.

The Government provides the initial WBS in the RFP package per MIL-STD-881C [23]. The contract WBS has detail added by the contractor, and is updated during the program. The WBS is the primary framework for program organization and reporting.

In risk exposure early warning, the WBS and the IMP are the key frameworks to identify areas of elevated risk. The initial IMP is prepared by the Government as part of the RFP package. The IMP is a 3-level indented list of events, accomplishments, and criteria. The IMP is the basis for IMS and Earned Value Management (EVM) reporting [24, 25]. EVM time, cost and progress reporting is at the “Work Package” level of the IMS.

The high-level IMS is provided by the Government in the RFP package. It contains the major program milestones dated from start of contract award, major program activities, and their dependencies. The contractor details the IMS activities to accomplish each event/accomplishment/criteria entry in the IMP. The IMS is updated monthly. At a minimum, the IMS has Work Packages for the next 12 months and Planning Packages thereafter. A Planning Package consists of 1 or more Work Packages. A Work

Package consists of one or more detail tasks. Ideally a detail task has a singularized product, and defined completion criteria, although this is not always true in practice.

The “Work Package” and “Planning Package” identifiers link the schedule to EVM reporting. Reliability, validity, bias and accuracy of EVM reporting are concerns, as is the resolution of activity decomposition, EVM reporting, and completion criteria.

For each activity, the IMS contains the following data fields: parent WBS element, IMP entry, Planning or Work Package; activity scheduling logical dependency relationships (predecessor-to-successor Finish-to-Start, Start-to-Start, Finish-to-Finish, and Start-to-Finish dependencies); budgeted time, budgeted cost, actual time expended, slack time, actual cost expended, fraction of work performed. Some of this information comes from the EVM system. Level-of-effort tasks are not included in the IMS. The IMS is the basis for schedule and cost risk analysis. The analysis can be for the overall program, by WBS element, and/or by IMP entry. By including maturity advancement steps in the IMP, cost and schedule of maturity advancement is tracked.

The SSS begins with the performance specification (P-Spec), a part of the RFP package. The SSS contains derived requirements for system segments of the contract WBS. The SSS contains the following fields: the WBS element (level 3 or below); the parent SSS elements (there may be more than one); the singular property or characteristic; the threshold and objective criteria (performance levels and conditions of performance), priority level (e.g. “tiers”), pointers to the verification tasks in the IMS (null if no task accomplishes verification); verification results (null if the verification task has not been completed, else the performance measure results and test conditions); method of verification (e.g., design inspection, analysis, bench testing, integrated testing), compliance (compliant, partially compliant, not compliant); estimate of achievable performance; tradespace dimension and tradeoffs (holistic system attribute tradespace gained or lost if the requirements are changed to the achievable level; e.g., size, weight, power, cooling, production cost, and impact on other performance requirements); time and cost of verification if there is not a verification task. Ideally, the SSS addresses the costs of compliance verification.

Compliance verification can be at different levels, e.g., design acceptance, manufacturing and design acceptance, modeling and simulation of design and manufacturing, system integration laboratory testing, field testing etc.

The information in the SSS is the essential information for tracking compliance progress, and for performance requirements trades against time, cost, and design tradespace. It provides information for time and cost tradeoffs versus verification to reduce risk. It tracks back to the IMS to correlate compliance with cost and schedule.

The SSS would benefit from a prior definition of the holistic attribute tradespace dimensions, e.g., extracted from the Ground System Architecture Framework [26], and linking the dimensions to the subsystems that supply and consume each resource. It would also benefit from a formalized definition of the levels of verification matched to the levels of the maturity level definition, e.g., verification by design review, subsystem modeling and simulation, subsystem testing in a laboratory environment, integrated system modeling and simulation, integrated system testing in representative context, full system integrated testing in a realistic context and environment.

The ST contains the technical baseline as it is developed during the program. It specifies the functional baseline, allocated baseline and product baselines [27]. Data structures, file formats, data fields and formats have not been standardized. The functional baseline describes the functional and interface characteristics of the overall system, and the verification required to demonstrate their achievement. The allocated baseline defines the lower-level configuration items making up a system, and how system function and performance requirements are allocated across lower level configuration items, including design constraints and the verification required to demonstrate the traceability and achievement of specified functional, performance, and interface characteristics. The product baseline describes the functional and physical characteristics of a configuration item; the selected functional and physical characteristics designated for production acceptance testing; and tests necessary for deployment/installation, operation, support, training, and disposal of the configuration item. The initial product baseline includes "build-to" specifications for hardware (product, process, material specifications, engineering drawings, and other related data), and “code to” specifications for software. Verification of completeness of the technical baselines is normally reviewed at technical reviews, as specified in the IMP.

The SA defines the physical and logical system entities with boundary diagrams and behaviors. Boundary diagrams specify entity relationships with each other and the external environment, and are supplemented with formatted data describing the characteristics of each interface. Behaviors are derived by tracing operational scenarios, vignettes, mission threads, and/or use cases through system boundaries to derive internal system behavior culminating with a linked and traceable allocation of behavior for product design and development. Specific guidelines for the system architecture and design documentation have distribution restrictions.

System architecture assessment can include technology, integration, and manufacturing readiness assessments. These assessments are for selected subsystems and technologies for CTE and OTI – not the entire system. Reporting TRL/IRL/MRL for all system architecture elements and levels of decomposition would support risk early warning across the entire system to reveal evidence of previously unforeseen risks. Restricting TRL/IRL/MRL assessment to CTEs and OTIs elevates the risk of being blindsided by unforeseen challenges and events. However detailed investigation of TRL/IRL/MRL and potential risks requires commitment of time, cost, and decision authority.

The TRC are filled out at each of the major reviews, based evidence presented at the review and judgment of the reviewers. The TRC probe the status of the technical program in thirteen areas with specific, predetermined questions [28]. Status is rated red, amber, green, unknown, or not applicable. The TRC cover many different factors, from “was a responsible person appointed to conduct and approve the review” to “what fraction of the critical requirements have been shown to have been met.”

The MCE contains estimates of the recurring and non-recurring costs, for each variant in the Family of Vehicles, against a detailed standardized Ground System Architecture. The Government provides the reporting framework. The contractor provides an update to the estimate at each major program review. All entries are initially rated “to be determined”.

INTEGRATED COST, SCHEDULE, AND PROGRAM TECHNICAL PERFORMANCE RLI

The Risk Working Group, led by the Army Materiel Systems Analysis Agency (AMSAA) identified lack of methods for integrated cost, schedule, and program technical performance risk assessment as their greatest concern and highest priority. Methods for cost and schedule risk analysis were not coupled with assessment and diagnosis of what the risk exposure meant for the technical performance of the acquisition program. Technology risk assessment methods ask for estimates of the time and cost consequences if identified future events occur, but not as part of integrated cost and schedule risk assessment.

In principle, cost and schedule risk analysis, using data provided in IMS and EVM reporting, can be used to analyze time and cost risk exposure by technology area, stage and extent of integration and incremental verification through developmental testing. But this is only possible if the activities in the IMS are mapped to design, integration, and test stages, by technology area. The mechanism for the mapping is the IMP. The Government specifies the IMP events, accomplishments and criteria as part of the RFP package. The IMP, together with the WBS, are the basis for the IMS and EVM reporting.

While the mechanism is available, the IMP has not traditionally been used to ensure that contract data reporting provides the information needed for integrated cost, schedule and technical program performance. Events, accomplishments, and criteria in the IMP typically include process steps for technical reviews (e.g., the PRD is an event, PDR preparation completed is an accomplishment, and proceeding to PDR approval by the SEIT is a criterion), as well as end-state events such as prototype deliveries and EMD test.

The IMP could be used to ensure that data in the IMS and EVM reports are suitable to assess risk exposure by technical area and advancement. The key is to define events, accomplishments, and criteria that correspond to significant system design and integration stages of advancement. We have developed two complementary methods. Both are relevant. They provide orthogonal views of program technical progress. One view is based on the WBS, the other is based on the design, manufacturing and RAM maturity levels as defined in the RFP attachments.

Using the WBS to Define Technical Progress Events

The WBS is an attachment to the RFP package. The Government defines the WBS. The WBS is the breakdown structure of what is to be developed and delivered under the contract. The WBS is broken down by functional component, e.g., automatic ammunition handling, navigation and remote piloting, etc. The WBS also includes system level activities such as integration, assembly, test, checkout, shipping, etc.

Completion of each functional component WBS line should become an event in the IMP. The accomplishments are design, integration, developmental testing, manufacturing development. The system level activities should also be included as events.

Cost and schedule reporting tagged to these events and accomplishments enables the risk analysis to (1) analyze cost and schedule risk of the functional components, then (2) identify the functional components contributing most to overall risk exposure. This creates the ability to analyze risk exposure by WBS functional component.

Using the Maturity Levels to Define Technical Progress Events

In the proposal evaluation, the maturity levels, and the substantiating data, are inputs to assess the relative risks of alternative proposals. As the program advances in system design, manufacturing and RAM maturity, risk is retired. Maturity advancement ends with delivery the completed product. The maturity level definitions can be used integrate time, cost, and technical advancement reporting and analysis by inserting maturity advancement steps into the IMP.

Maturity advancement can be inserted into the IMP by adding three events: design maturity advancement, manufacturing maturity advancement, and RAM maturity advancement. The following notional example illustrates how the maturity advancement could be resolved into IMP events, accomplishments and criteria, thus forcing traceable linkage between technical progress, time, and cost.

The accomplishments are stages of maturity advancement towards completion for design, manufacturing, and RAM.

The design maturity accomplishments and criteria are design and development artifacts and test results, corresponding to major technical reviews [29] and test & evaluation events [30]. The manufacturing maturity accomplishments and criteria are drawn from the manufacturing readiness handbook [31]. The RAM maturity accomplishments and criteria are drawn from the design for reliability handbook [32].

Event: System Design Maturity Advancement

- Accomplishment 1: Requirements. Criteria: Completion of (a) requirements decomposition, (b) functional baseline, (c) derived requirements development, and (d) interface identification
- Accomplishment 2: Preliminary Design. Criteria: Completion of (a) allocated baseline, (b) component analysis and selection, (c) CAD models, (d) mass properties models, (e) load plan models, (f) hull/structure/frame finite element models, (g) powertrain and mobility models, (h) survivability models, and (i) interface models
- Accomplishment 3: Critical Design. Criteria: Completed sub-system architecture, design, integration and testing in the an integration lab for product WBS Configuration Items
- Accomplishment 4: System Integration & Test Readiness. Criteria: Completed sub-system integration, testing, analysis of deficiencies, and corrective measures in an operationally relevant environment for product WBS Configuration Items
- Accomplishment 5: Prototype Delivery and Operational Testing. Criteria: (a) delivery of prototypes, (b) completion of Operation Testing, (c) corrective action plans for residual deficiencies
- Accomplishment 6: Production Readiness and System Verification. Criteria: Completion of (a) final design, (b) Technical Data Package with CAD models, mass properties models, loading plan/model, and bill of materials, (c) live fire test

Event: Manufacturing Maturity Advancement

- Accomplishment 1: Manufacturing Concept. Criteria: Completed (a) initial manufacturing and process models, (b) materials acquisition approach
- Accomplishment 2: Manufacturing Requirements Analysis. Criteria: Completed identification of (a) manufacturing concepts, (b) producibility needs, (c) new manufacturing processes, (d) new manufacturing skills, (c) special facility requirements, (f) supply chain requirements
- Accomplishment 3: Preliminary Manufacturing Analysis. Criteria: Completed identification of (a) manufacturing modeling and simulation approaches, (b) lead times for materials, (c) exotic materials (hazardous, difficult to obtain and/or process), and (d) supply chain model and potential sources
- Accomplishment 4: Detailed Manufacturing Analysis. Criteria: Completed (a) modeling and simulation analysis at the component and subsystem levels to determine constraints, (b) assessment of issues, performance and reliability of similar full production processes, (c) identification of skill sets, special skills training and certification, (d) selection of supply chain sources
- Accomplishment 5: Manufacturing Feasibility Verification. Criteria: Completed verification of (a) the manufacturing processes in a production relevant environment, (b) availability of workforce skills, (c) adequate facilities and/or facility development plans, (d) long-lead items identified, (e) obsolescence/disposal issues identified, (f) supply chain and supplier agreements in place
- Accomplishment 6: Full Manufacturing Verification. Criteria: Completed (a) demonstration of manufacturing processing in a production relevant environment, (b) specification of manufacturing workforce resource requirements (staffing and floor managers), (c) specification of facility capabilities, (d) long-lead item procurement plan, (e) obsolescence plan

<u>Event: RAM Maturity Advancement</u>

- Accomplishment 1: Requirements Analysis. Criteria: Completed (a) reliability continuous improvement plan to meet reliability and maintainability requirements, (b) reliability (mean miles between system abort) and maintainability (maintenance ratio, mean time to repair, max-time to repair) allocated down to the Line Replaceable Unit (LRU) level
- Accomplishment 2: Preliminary Design Analysis. Criteria: Completed (a) design failure modes and effects analysis (DFMEA), (b) Fault Tree Analysis (FTA) for all essential functions listed in the Failure Definition and Scoring Criteria, (c) Critical Items List – items whose failure would cause a mission failure or Category III or higher Hazard Severity Rating as defined in MIL-STD-882D, (d) reliability and maintainability estimates made at the LRU level, (e) initial reliability growth plan and curve (per AMSAA Projection Maturity Model)
- Accomplishment 3: Integrated Subsystem Reliability. Criteria: Completed modeling and simulation and/or sub-system testing to estimate the reliability of integrated sub-system operation
- Accomplishment 4: Detailed Design Analysis. Criteria: Using integrated subsystem reliability date from Accomplishment 3, completed (a) updated DFMEA, (b) updated FTA, (c) updated reliability and maintainability estimates, (d) reliability growth plan and curve, and (e) Failure Reporting and Corrective Action System (FRACAS) report
- Accomplishment 5: System Level Testing. Criteria: Completed (a) reliability, maintainability, and durability test plan, (b) testing the specified number of miles on the operational terrain profile, (c) test report with details of the driving profile, terrain profile, times and types of failures
- Accomplishment 6: Post Testing Detailed Design Analysis. Criteria: Using system level testing data from Accomplishment 5, completed (a) updated FRACAS report identifying failure modes, root causes, corrective actions, and validation, (b) updated reliability and maintainability predictions, and (c) updated reliability growth plan and curve
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RISK LEADING INDICATORS

Risk Leading Indicators are computed from baseline and update program management and systems engineering data. RLI assess the current status, as well as trends and instability.   They assess (1) the change from the initial baseline, and (2) the change from the last update. This requires that the Systems Engineering system retain initial baselines and previous state. This is the minimum information to assess current state, short- and long-term trends. The reporting process samples the state of the system in periodic updates (e.g., monthly) and event-based updates (e.g., technical reviews). Early warning of risk exposure and emerging risk exposure requires early visibility into the state of the system and its progress. Waiting until late-stage technical reviews to identify issues exposes the program to risk.

The initial list of candidate Risk Leading Indicators follows. The RLI address requirements, maturity, design (baselines, architecture, and design margins), technical reviews, plan and schedule.

- Requirements Interdependency. Number of requirements, number of dependencies between requirements, ratio
- Requirements Stability. Proportion of requirements and dependencies that were (a) added, (b) deleted, and (c) changed
- Requirements Verification. Proportion of requirements with compliance verification activities in the IMS, number that have been verified, number that were fully/partially/not compliant, number of requirements linked to requirements that were fully/partially/not compliant

- Requirements Verification Schedule. Minimum and average schedule slack for remaining verification activities, minimum and average project time remaining after scheduled verification activities
- Maturity. Design, manufacturing and RAM maturity levels, difference between scheduled level and achieved level (at the criteria, accomplishment, and event levels)
- Manufacturing Cost Maturity. Proportion of applicable entries in the MCE that are blank or "to be provided", the proportion of entries with different values than the previous submittal; percentage change in the estimated unit production cost
- Baselines. Number of entries in the functional, allocated, and product baselines, number of links to requirements, number of links to architecture elements, ratios of changes to number in each baseline
- Architecture. Numbers of architecture elements and links between elements, proportion without completed boundary diagrams, proportion with changed boundary diagrams
- Design Margins. Design margin remaining as a proportion of the base, for each holistic system parameter (ground vehicle holistic system parameters are found in the Ground System Architecture Framework [26], e.g., mass properties, volume, dimensions, surface areas, main and auxiliary power, cooling capacity, fuel consumption, etc.)
- Technical Reviews. Total and by major sub-heading the number of applicable fields, for the applicable fields, the proportion rated red, amber, green, and unknown, number of changes from unknown to known, proportions of increases and decreases in level and from unknown to known and known to unknown
- Integrated Master Plan (IMP) Stability. Number of IMP entries, proportion added, deleted, or changed
- Integrated Master Schedule (IMS). Number of IMS activities (by Planning Package, Work Package, and detail task), number of dependencies (by logical type), ratio of links to nodes, proportion of activities completed, begun, started or finished out of sequence with their dependencies, mean and variance of the ratio of actual to planned duration for completed activities, float on the critical path relative to the critical path to each milestone, number of "high risk" activities (i.e., with ratio of float to scheduled duration is less than X percent)
- Schedule Stability. Numbers and proportions of activities and dependencies that were (a) added, (b) deleted, and (c) changed

Areas of High Relative Risk

Risk Leading Indicators can be computed for the entire program and system to assess overall risk exposure, and by segment to diagnose areas of high risk exposure. Different RLI are decomposed in different ways that give different insight into the areas at risk. Requirements RLI are linked to priority tier, and branch of the specification tree. Maturity RLI are linked to acquisition phase (development, manufacturing, and sustainment) and major subsystem. Design RLI are organized by product WBS. Schedule RLI are linked to WBS element, and by IMP entry. Technical review checklists have their own organization.

Risk Leading Indicators that are correlated can be combined using Principal Components Analysis to reduce the number of indicators and variability. This requires an accumulation of data points.

Predicting future time, cost, performance differences between actual and planned results (assuming that past relationships between RLI and subsequent outcomes will persist) requires an accumulation of data points by IMS activity.

Some decisions need to be made before there has been enough history to compute trend and stability metrics, and before there has been time to accumulate data to calibrate statistical RERs. "Shortcut" methods are needed to assess relative risk (a) in proposal evaluation without "trend and stability" data, (b) during contract execution but without sufficient history to quantify time, cost, and performance bias and dispersion, and (c) when there is insufficient data to project bias and dispersion of outcome.

The underlying concept is to find outliers, e.g., WBS elements with high levels of RLI relative to other WBS elements. Even without data to quantify the relationship between RLI and time, cost, performance outcome, it is still possible to identify WBS elements with elevated RLI – e.g. if one proposal or WBS element has RLI that are three standard deviations above the norm, it is higher risk than one whose RLI are one standard deviation above the norm.

RISK ESTIMATING RELATIONSHIPS (RERS)

RERs are equations or models. The RLI are the inputs. Time, cost and performance bias and uncertainty are outputs. RERs are calibrated to program data on time, cost, and performance by IMP entry, WBS element, and the overall program. Calibration uses historical data on the program to compute model coefficients. Differences between IMP entry, WBS element, and entire program provide insight into the sources of risk exposure.

Risk Estimating Relationships are essentially regression models that explain future IMS activity cost and schedule bias and dispersion in terms of current risk leading indicators. RERs are similar to Cost Estimating Relationships (CERs) used in parametric, analogy cost models. RERs are statistically significant relationships that explain program performance as functions of earlier RLI.

The RER are calibrated to previous period data for the current program. Program-to-program differences make it unlikely that quantitative evidence from one program will be relevant to another program with different design challenges, performance objectives, contractor management, engineering team, etc. The RER contain autoregressive components (past trends predict future trends) and logical components (incompleteness, instability, inconsistency, lack of safety margins, interdependency in the current state predict deficiencies in future outcomes).

Program performance data are accumulated over time. At proposal evaluation, only uncertainties inherent in the RFP package and the proposals can be assessed. After contract award, data can be accumulated regarding input conditions and output results, by IMP entry, WBS, and overall program.

Each completed activity in the IMS constitutes a data point with a cost and schedule variance. Completed requirements verification tasks also provide compliance variance. Each IMP event is a data point.

Regression models include all computational methods that use historical data to fit a type of model between input and output variables. Candidate regression methods include linear, multi-linear, non-linear, locally linear, and adaptive statistical regression. Other statistical estimation frameworks include naïve Bayes models and families of multi-dependency Bayes models with fixed or adaptive weighting.

The choice of underlying RER models is pragmatic – the formalism that works best is best to explain progress variances. Previous programs can suggest high value models and parameters, but differences among program may reduce relevance.

The question is which methods work – in practice, for this application – not which are best in theory. The characteristics of the application are complex. Different programs will have different challenges.

This makes extrapolating from on program to another problematic. There are a large number of potential risk exposure indicators. In any given program, at any stage of the program (punctuated by the major technical reviews), and divided by the WBS elements, different indicators can have different significance. Outcome states can be positively or negatively correlated. EMD time and cost tend to be positively correlated, and negatively correlated with system performance, production cost and RAM.

The large number of IMS activities provide data to correlate WBS/IMP/IMS time/cost expenditure and technical accomplishment to the RLI (e.g., IMS limited to 6,000 detail tasks). The semi-hierarchical lattice structure of requirements, program activities, system segments, and system architecture pose challenges to statistical analysis, as does potential differences in the program between technical review milestones and level 3 WBS elements.

2015 OBJECTIVES, APPROACH, PLANS AND SCHEDULE

OBJECTIVES AND APPROACH

The primary objective for 2015 is to "stress-test" the RLI via pilot application to an EMD-phase MDAP, and potentially to a pre-EMD phase program. Different RLI apply at pre-EMD and EMD stages.

The pilot applications will be used to refine & adapt the RLI, to demonstrate and assess their value to the program, and to identify potential issues that might impede transition into general use. The pilot applications will be conducted in collaboration with the programs' Risk Managers, and the TARDEC Risk Management team. We met with the MDAP Risk Manager and TARDEC risk management team in early February 2015, to review and refresh our collaboration agreement following contract award and exit from Source Selection in late December 2014. Specifics of the plans to pilot the EMD-phase RLI on the MDAP are described in the following section.

We have a meeting scheduled in late February 2015 to meet with the pre-EMD "Future Tank" team (PM Abrams) to discuss collaboration. The "Future Tank" program is a significant upgrade to the Abrams tank, with increased modularity for potential to integrate advanced technologies as they mature. This report is being prepared prior to the meeting. There is potential to open discussions with the CVP (Combat Vehicle Prototype) technology demonstration project at TARDEC, although we have no plans to do so at this time. The CVP is an evolution of the Ground Combat Vehicle (GCV), pushed back to a Technology Demonstration project vice a MDAP.

A secondary objective is to communicate the RLI MPT and the pilot application emerging results to the broader user and developer community. The will be accomplished through a series of discussions and presentations, culminating in a workshop at the end of the year. The intended audience of the workshop includes end-users such as AMSAA and Risk Management Teams from RDECOM elements outside of TARDEC, and other service components, as well as developers and theoreticians from groups such as RAND, IDA, and MITRE. This will be a continuation and extension of the technical exchanges held during 2014.

A third objective is to begin to develop RLI that are specific development risks associated with software-intensive cyber-physical systems with real-time, distributed, embedded processing interacting with sensor, actuator, communications hardware, and the external system dynamics. This will be accomplished by building on RLI findings in 2014, related research on other research tasks, and coordinating with DASD-SE personnel with related objectives and responsibilities.

Preliminary findings indicate that the number and density of interconnections and interdependencies among the cyber-physical components is a driving factor in development time and cost, and potential needed for rework to correct for unforeseen omissions and interactions [33, 34, 35]. The experience of the technical management and engineering leads with similar systems is another important factor in time and cost estimating accuracy and uncertainty. The challenge is to develop risk leading indicators is to forecast the density of interconnections and interdependencies of the eventual system design during earlier the conceptualization and requirements formulation stages.

EMD-PHASE RLI PILOT APPLICATION PLANS

2014 we established a collaboration agreement with an MDAP (under PEO GCS) to pilot the RLI on the program, provided

(1) that we would coordinate with and provide feedback to the risk manager so that the program would receive the benefits

(2) that we would work with data and reports that the program could provide with minimal additional cost or effort

(3) that the support to the program would be sustained collaboration vice a "one-off" study, and

(4) that we collaborate with TARDEC so that the finding and results would transition to the end-user community.

At the time of the agreement, the program was about to enter Source Selection, at which point communication with the PMO was to be suspended in order to prevent possible legal complications. The contract was awarded in late December 2014, with a start-of-work meeting in January 2015. During this time, the PMO was reorganized and a new Risk Manager was assigned. We held an "re-start" meeting with the Risk Manager and TARDEC Risk Management team in early February 2014, with a collaboration launch meeting planned for early March 2015. The AMPV PDR is scheduled for June, 2015, with CDR in summer, 2016.

The current plan is to brief the PM or his deputy, and the Risk Manager, in March 2015 on (1) risks embedded in the RFP package and how they can be mitigated, and (2) plans to support the Risk Manager via piloting the RLI. The briefing will define specific contract data reporting items we request, and explain how they will be used to evaluate which specific RLI, and the significance of the RLI. The briefing will also explain the collaboration plan. The current collaboration plan is to receive monthly updates to the CDRI from the PMO, and to provide quarterly briefings to the Risk Manager. In addition to regular quarterly briefings, we will participate in risk management meetings, as needed to examine specific risk exposure evidence and potential mitigation.

Contract Data Reporting Items

Only unclassified, non-proprietary, contract data reporting items will be used, whose distribution control statement allows release to Government contractors. Initial releases and their periodic updates are needed so that the RLI will reflect the current status and trends in the program. The data items of interest, as currently identified, are:

- Contractor Work Breakdown Structure (CWBS) – an elaboration of the Government WBS
- Contractor Systems Engineering Management Plan (SEMP – which documenting the Integrated Product Teams and team experience and other important Systems Engineering factors)
- Contractor Integrated Master Plan (IMP) – an elaboration of the Government IMP
- Contractor Integrated Master Schedule (IMS) – documenting the planned chains of events and activities, durations, and current status of the program, linked to the WBS and IMP
- Earned Value Management (EVM) reports on the budgeted cost of work performed, actual cost of work performed, and proportion of work performed at the "work package" level of the IMS

- Selected proposal and system description sections – as referenced in the “Matrix of Substantiating Data for System Design Maturity, Manufacturing, and RAM” (RFP attachment 0052)

- Manufacturing cost estimates (per the template in RFP attachment 0067)

- Risk register (list and status of currently identified risks, per the Risk Management Plan, RFP attachment 002)

- System Architecture Description Document (SADD, per RFP attachment 0104, Integrated System Architecture Modeling Guide, RFP attachment 0087, and Ground System Architecture Framework, RFP attachment 0030)

- Technical review checklists when completed following technical reviews

High Value and Second Tier RLI

In discussions with the Risk Manager several areas of concern and applicable RLI were discussed.

Integrated cost, schedule and technical progress risk was a major concern. Program cost and schedule risk analysis were not linked to measures of technical progress (i.e., maturity level advancement) and technical areas (i.e., WBS elements). In order to apply the RLI and RER formulated to address this issue, we need to map the IMS activities to the maturity levels and WBS elements. These links need to be built. Important RLI are

(1) the cost and schedule bias and uncertainty by maturity level and WBS element

(2) the risk to overall project cost and schedule, by maturity level and WBS element

The Risk Manager acknowledged that the schedule risk assessment as described in the RFP package was limited, and did not provide adequate insight into schedule risk. Schedule risk analysis is needed to addresses high risk paths (not just the critical path and the impact of uncertainty on the critical path), and identify IMS activities with a large role in overall schedule risk. The schedule RLI are appropriate to provide this additional insight and early warning.

Second tier RLI address completeness and stability of various plans and estimates, specifically the manufacturing cost estimate, the system architecture, and the IPT composition. The completeness of IPTs matching the convergence of parallel paths in the IMS was also discussed as evidence of presence of risk mitigation via the IPTs.

As a point of interest, we also discussed the potential value of examining the correlation between the RLI and (a) risks identified through the standard risk management process, and (b) technical review checklists when completed.

2015 Schedule of Major Events

February 2015

- Deliver final report on 2014
- Reconnection meeting with AMPV Risk Manager
- Initial meeting with PM Abrams “Future Tank” team

March 2015

- Phase III Kickoff Meeting or Teleconference with DASD-SE
- Brief the MDAP PMO on collaboration plans, risks embedded in the RFP, and mitigations
- Initiate piloting EMD-phase RLI on the MDAP as source material is received
- Initiate piloting pre-EMD RLI on “Future Tank” as source material is received

April 2015

- Teleconference with Sean Brady DASD-SE, MPS on risk indicators for software-intensive cyber-physical systems with real-time embedded, distributed processing coupled to sensor, actuator and communications hardware

May 2015

- Quarterly meeting with the MDAP Risk Manager and TARDEC Risk Management liaison
- Quarterly meeting with “Future Tank” and TARDEC Risk Management liaison
- Quarterly teleconference with DASD-SE, Major Program Support

August 2015

- Quarterly meeting with the MDAP Risk Manager and TARDEC Risk Management liaison
- Quarterly meeting with “Future Tank” and TARDEC Risk Management liaison
- Quarterly teleconference with DASD-SE, Major Program Support

September 2015

- Teleconference with Sean Brady, DASD-SE, MPS on risk indicators for software-intensive cyber-physical systems with real-time embedded, distributed processing coupled to sensor, actuator and communications hardware

November 2015

- Quarterly meeting with the MDAP Risk Manager and TARDEC Risk Management liaison
- Quarterly meeting with “Future Tank” and TARDEC Risk Management liaison
- Quarterly teleconference with DASD-SE, Major Program Support

December 2015

- Workshop on Risk Leading Indicators inviting AMSAA, et. al.
- Annual meeting with and presentation to DASD-SE, MPS

February 2016

- Deliver final report on 2015
- Quarterly meeting with AMPV Risk Manager and TARDEC Risk Management liaison
- Quarterly meeting with “Future Tank” and TARDEC Risk Management liaison

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