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TENTH ANNUAL ACQUISITION
RESEARCH SYMPOSIUM
COST ESTIMATING

Quantifying Uncertainty for Early Life Cycle Cost Estimates

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Software Engineering Institute

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ACQUISITION RESEARCH PROGRAM
GRADUATE SCHOOL OF BUSINESS & PUBLIC POLICY
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Preface & Acknowledgements

Welcome to our Tenth Annual Acquisition Research Symposium! We regret that this year it will be a “paper only” event. The double whammy of sequestration and a continuing resolution, with the attendant restrictions on travel and conferences, created too much uncertainty to properly stage the event. We will miss the dialogue with our acquisition colleagues and the opportunity for all our researchers to present their work. However, we intend to simulate the symposium as best we can, and these *Proceedings* present an opportunity for the papers to be published just as if they had been delivered. In any case, we will have a rich store of papers to draw from for next year’s event scheduled for May 14–15, 2014!

Despite these temporary setbacks, our Acquisition Research Program (ARP) here at the Naval Postgraduate School (NPS) continues at a normal pace. Since the ARP’s founding in 2003, over 1,200 original research reports have been added to the acquisition body of knowledge. We continue to add to that library, located online at www.acquisitionresearch.net, at a rate of roughly 140 reports per year. This activity has engaged researchers at over 70 universities and other institutions, greatly enhancing the diversity of thought brought to bear on the business activities of the DoD.

We generate this level of activity in three ways. First, we solicit research topics from academia and other institutions through an annual Broad Agency Announcement, sponsored by the USD(AT&L). Second, we issue an annual internal call for proposals to seek NPS faculty research supporting the interests of our program sponsors. Finally, we serve as a “broker” to market specific research topics identified by our sponsors to NPS graduate students. This three-pronged approach provides for a rich and broad diversity of scholarly rigor mixed with a good blend of practitioner experience in the field of acquisition. We are grateful to those of you who have contributed to our research program in the past and encourage your future participation.

Unfortunately, what will be missing this year is the active participation and networking that has been the hallmark of previous symposia. By purposely limiting attendance to 350 people, we encourage just that. This forum remains unique in its effort to bring scholars and practitioners together around acquisition research that is both relevant in application and rigorous in method. It provides the opportunity to interact with many top DoD acquisition officials and acquisition researchers. We encourage dialogue both in the formal panel sessions and in the many opportunities we make available at meals, breaks, and the day-ending socials. Many of our researchers use these occasions to establish new teaming arrangements for future research work. Despite the fact that we will not be gathered together to reap the above-listed benefits, the ARP will endeavor to stimulate this dialogue through various means throughout the year as we interact with our researchers and DoD officials.

Affordability remains a major focus in the DoD acquisition world and will no doubt get even more attention as the sequestration outcomes unfold. It is a central tenet of the DoD’s Better Buying Power initiatives, which continue to evolve as the DoD finds which of them work and which do not. This suggests that research with a focus on affordability will be of great interest to the DoD leadership in the year to come. Whether you’re a practitioner or scholar, we invite you to participate in that research.

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

- Office of the Under Secretary of Defense (Acquisition, Technology, & Logistics)
- Director, Acquisition Career Management, ASN (RD&A)
- Program Executive Officer, SHIPS
- Commander, Naval Sea Systems Command
- Program Executive Officer, Integrated Warfare Systems
- Army Contracting Command, U.S. Army Materiel Command
- Office of the Assistant Secretary of the Air Force (Acquisition)
- Office of the Assistant Secretary of the Army (Acquisition, Logistics, & Technology)
- Deputy Director, Acquisition Career Management, U.S. Army
- Office of Procurement and Assistance Management Headquarters, Department of Energy
- Director, Defense Security Cooperation Agency
- Deputy Assistant Secretary of the Navy, Research, Development, Test, & Evaluation
- Program Executive Officer, Tactical Aircraft
- Director, Office of Small Business Programs, Department of the Navy
- Director, Office of Acquisition Resources and Analysis (ARA)
- Deputy Assistant Secretary of the Navy, Acquisition & Procurement
- Director of Open Architecture, DASN (RDT&E)
- Program Executive Officer, Littoral Combat Ships

James B. Greene Jr.	Keith F. Snider, PhD
Rear Admiral, U.S. Navy (Ret.)	Associate Professor

Cost Estimating

Software Should-Cost Analysis With Parametric Estimation Tools

Robert Ferguson
Software Engineering Institute

The Use of Inflation Indexes in the Department of Defense

Stanley A. Horowitz, Alexander O. Gallo, Robert J. Shue, Daniel B. Levine, and Robert W. Thomas
Institute for Defense Analyses

Political Connections of the Boards of Directors and Defense Contractors' Excessive Profits

Chong Wang
Naval Postgraduate School

An Analytical Synopsis of Dr. Ashton Carter's "Should-Cost" Initiatives

Cory Yoder
Naval Postgraduate School

Quantifying Uncertainty for Early Life Cycle Cost Estimates

Jim McCurley, Bob Ferguson, Dennis Goldenson, Robert Stoddard, and David Zubrow
Software Engineering Institute

Quantifying Uncertainty for Early Life Cycle Cost Estimates[1]

Jim McCurley—McCurley is a senior member of the technical staff at the Software Engineering Institute (SEI). During his 15 years at the SEI, his areas of expertise have included data analysis, statistical modeling, and empirical research methods. For the last several years, he has worked with various DoD agencies involved with the acquisition of large-scale systems. From 1999–2005, McCurley also worked as a member of the technical analysis team for the CERT Analysis Center. [jmccurle@sei.cmu.edu]

Robert Ferguson—Ferguson is a senior member of the technical staff at the Software Engineering Institute (SEI). He works primarily on software measurement and estimation. He spent 30 years in the industry as a software developer and project manager before coming to the SEI. His experience includes applications in real-time flight controls, manufacturing control systems, large databases, and systems integration projects. He has also frequently led process improvement teams. Ferguson is a senior member of IEEE and has a Project Management Professional (PMP) certification from the Project Management Institute (PMI). [rwf@sei.cmu.edu]

Dennis Goldenson—Goldenson joined the Software Engineering Institute (SEI) in 1990 after teaching at Carnegie Mellon University since 1982. An ACM and IEEE senior member, his work on measurement and analytical methods has focused on modeling performance and quality outcomes of software intensive systems. Recent work, in addition to QUELCE and calibration of expert judgment, includes systems engineering effectiveness, requirements engineering, the empirical evaluation of software architecture, and statistical methods to ensure data quality. Related interests are in voice of customer methods, tools to support collaborative processes, the quantitative analysis of textual information, experimental design, survey research methods, and the visual display of quantitative information. [dg@sei.cmu.edu]

Robert Stoddard—Stoddard is a principal engineer at the Software Engineering Institute (SEI). He earned a BS in business and an MS in systems management and is a certified Motorola Six Sigma Master Black Belt. He delivers measurement courses in public and client offerings and provides measurement consulting to external clients. [rws@sei.cmu.edu]

David Zubrow—Zubrow is the chief scientist for the Software Engineering Process Management (SEPM) program, where he is responsible for formulating research strategy, guiding the development of proposals, and representing the program's research activities and interests. Zubrow is also the manager of the Software Engineering Measurement and Analysis initiative at the SEI, which focuses

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[1]
This material is based upon work funded and supported by the Department of Defense under Contract No. FA8721-05-C-0003 with Carnegie Mellon University for the operation of the Software Engineering Institute, a federally funded research and development center.

DM-0000240

on empirical research and the development and application of quantitative techniques to software engineering problems. [dz@sei.cmu.edu]

Abstract

Extensive cost overruns in major defense programs are common, and studies have identified poor cost estimation as a main contributor. Research and experience have identified several factors associated with poor cost estimates. These include

- optimistic expectations about the program scope and technology that can be delivered on schedule and within budget;
- the enormous amount of unknowns and uncertainty that exist when these estimates are made about large-scale, unprecedented systems that take years to develop and deploy; and
- the heavy reliance, of necessity, on expert judgment.

In this paper, we describe a new, integrative approach for pre–Milestone A cost estimation called quantifying uncertainty in early life cycle cost estimation (QUELCE). QUELCE synthesizes scenario building, Bayesian belief network (BBN) modeling, and Monte Carlo simulation into an estimation method that quantifies uncertainties, allows subjective inputs, visually depicts influential relationships among change drivers and outputs, and assists with explicit description and documentation underlying an estimate. We use scenario analysis and dependency structure matrix (DSM) techniques to limit the combinatorial effects of multiple interacting program change drivers to make modeling and analysis more tractable.

Finally, we describe results and insights gained from applying the method retrospectively to a major defense program.

Background

The inaccuracy of cost estimates for developing major Department of Defense (DoD) systems is well documented, and cost overruns have been a common problem that continues to worsen (GAO, 2011, 2012). Because estimates are now prepared much earlier in the acquisition life cycle, well before concrete technical information is available, they are subject to greater uncertainty than they have been in the past (RAND, 2007). Early life cycle cost estimates are often based on a desired capability rather than a concrete solution. Faced with investment decisions based primarily on capability, several problems emerge when creating estimates at this early stage (Roper, 2010):

- *Limited Input Data:* The required system performance, the desired architecture of the solution, and the capability of the vendors are not fully understood.
- *Uncertainties in Analogy-Based Estimates:* Most early estimates are based on analogies to existing products. While many factors may be similar, the execution of the program and the technology used as part of the system or to develop it are often different. For example, software product size depends heavily on the implementation technology, and the technology heavily influences development productivity. Size and productivity are key parameters for cost estimation.
- *Challenges in Expert Judgment:* Wide variation in judgment can exist between experts, and the confidence in the input that they provide is generally not quantified and unknown.

- *Unknown Technology Readiness:* Technology readiness may not be well understood, and is likely to be over- or underestimated.

This paper describes the QUELCE method and experiences to date.

An Improved Method for Early Life Cycle Cost Estimation

The quantifying uncertainty in early life cycle cost estimation (QUELCE) method is an integrative approach for pre–Milestone A cost estimation to address the problems associated with early life cycle cost estimation while at the same time providing benefits not found in current cost estimation methods (Ferguson et al., 2011). The method aims to provide credible program cost estimates as distributions rather than point estimates. QUELCE produces intuitive visual representations of the data that explicitly model influential relationships and interdependencies among the drivers on which the estimates depend. Assumptions and constraints underlying the estimates are well documented, which contributes to better management of cost, schedule, and adjustments to program scope as more is learned and conditions change. Documenting the basis of an estimate facilitates updating the estimate during program execution and helps others make informed judgments about estimation accuracy.

The QUELCE method differs from existing methods because it

- uses available information not normally employed for program cost estimation,
- explicitly models uncertainty on the input side of the cost estimation equation in terms of program change drivers,
- enables calculation (and re-calculation) of the cost impacts caused by changes that may occur during the program life cycle, and
- enhances decision-making through the transparency of the assumptions going into the cost estimate.

Figure 1 shows the flow of information in a typical major defense acquisition program (MDAP) acquisition, with blue boxes added to represent the contributions from the QUELCE method.

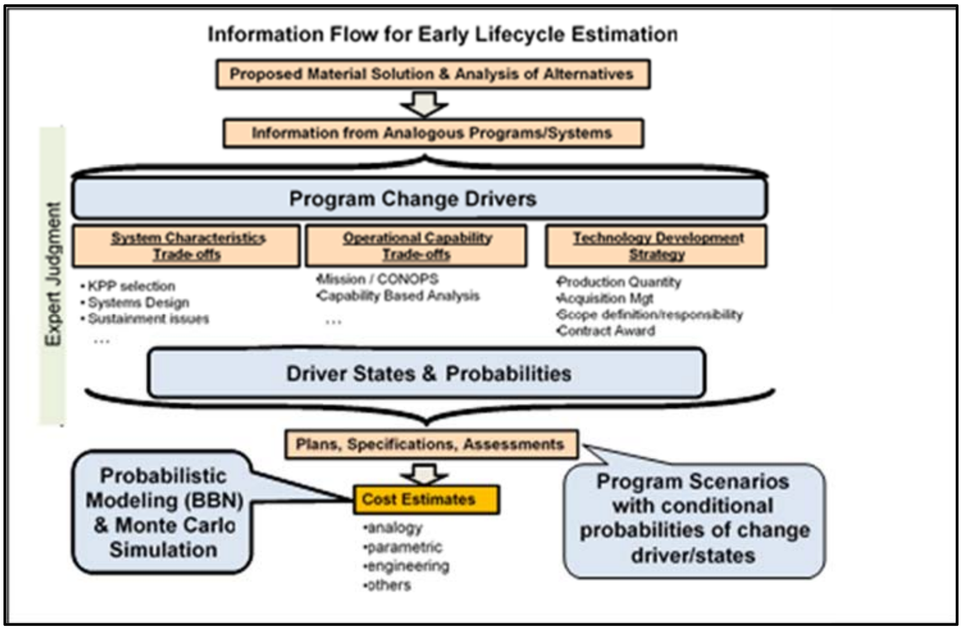

Figure 1. Information Flow for Early Life Cycle Estimation, With QUELCE Method Additions

The QUELCE Method

QUELCE synthesizes scenario building, Bayesian belief network (BBN) modeling, and Monte Carlo simulation into an estimation method that quantifies uncertainties, allows subjective inputs, visually depicts influential relationships among change drivers and outputs, and assists with the explicit description and documentation underlying an estimate. It uses scenario analysis and dependency structure matrix (DSM; Lindemann, n.d.) techniques to eliminate cycling among the interacting program change drivers to make modeling and analysis more tractable. Representing scenarios as BBNs enables sensitivity analysis, exploration of alternatives, and quantification of uncertainty.

The BBNs and Monte Carlo simulation are used to predict variability of what become the inputs to the existing cost estimation models and tools. As a result, interim and final cost estimates are represented as distributions so that the decision-maker can see the probability of a program exceeding the specified cost. The method can be described as a series of five activities, summarized in the following sections.[2]

Identify Program Change Drivers

The identification of program change drivers is best accomplished by the experts who provide programs with information about acquisition, development, and the technical approach, in addition to direct input for cost estimation. A workshop setting is used to identify drivers that could affect program costs. These experts consider all aspects of a program that might change and significantly affect its execution during the program's life cycle—particularly given the new information developed during the Technology Development Phase in preparation for Milestone B. The probability of program success (POPS) factors used by the Navy and Air Force can be used to start the brainstorming and discussion.

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[2] This work was originally described in a two-part series on the SEI blog, A New Approach for Developing Cost Estimates in Software Reliant Systems (http://blog.sei.cmu.edu/post.cfm/improving-the-accuracy-of-early-cost-estimates-for-software-reliant-systems-first-in-a-two-part-series).

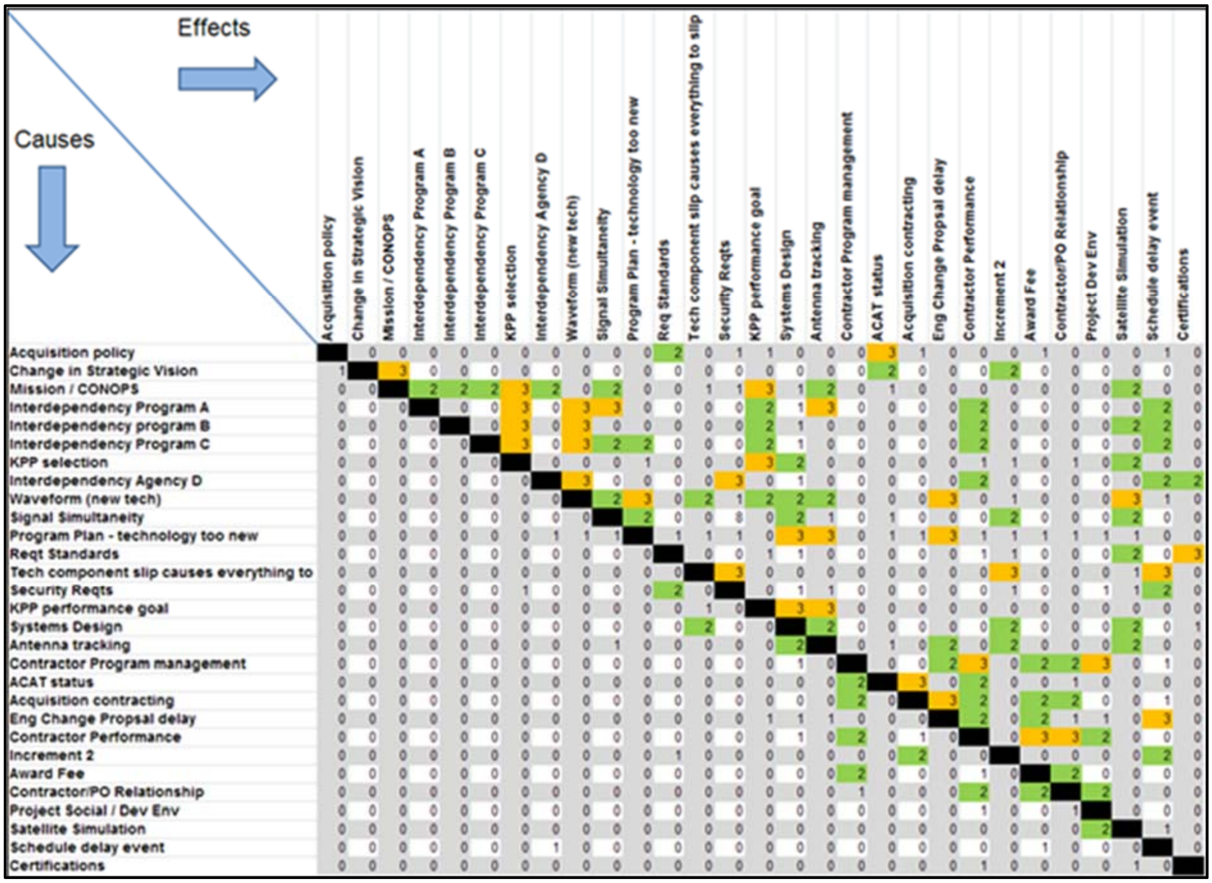
In support of this step, we have found that there is much useful information contained in a variety of documents produced during the pre–Milestone A phase. These include the Analysis of Alternatives and the various reports and documents developed as part of the Materiel Solution, the Technology Development Strategy, and, where available, any pre–Milestone A assessments such as the POPS gate reviews. While these traditionally have not been considered for cost estimation purposes, during the conduct of a retrospective study, we found these and other program documents to contain relevant information suggesting several program change factors. Our initial list totaled nearly 60 factors.

In the workshops, experts are asked to provide judgments about the status of each program change driver. The specific, assumed state as proposed by the Materiel Solution and Technology Development Strategy is identified and labeled as the nominal state. Experts then brainstorm about possible changes in the condition of each driver that may occur during the program life cycle. The experts identify possible changes that might occur to the nominal state and use their best judgment for the probability that the nominal state will change.

Identify Interdependencies and Reduce Complexity

Once the changed conditions—referred to as potential driver states—are fully identified, participants subjectively evaluate the cause and effect relationships among the drivers. Expert judgment is applied to rank the causal effects. A matrix is developed that provides the relationship between nominal and dependent states and contains the conditional probability that one will affect the other, but not the impact of the change. This exercise can result in a very large number of program change drivers and states identified for an MDAP.

Using dependency structure matrix (DSM; Lindemann, n.d.) techniques, the highly rated change drivers in the matrix can be reduced to an efficient set that has the most potential impact to program execution and, hence, cost. The DSM technique is a well-established method to reduce complicated dependency structures to a manageable size. Furthermore, the technique helps to eliminate cycles in the matrix by transforming the matrix to an upper-right triangle and makes it directly useful for constructing the BBN. An example of a dependency matrix after DSM transformation created during an SEI workshop is provided in Figure 2.



Effects Causes	Acquisition policy	Change in Strategic Vision	Mission / CONOPS	Interdependency Program A	Interdependency Program B	Interdependency Program C	KPP selection	Interdependency Agency D	Waveform (new tech)	Signal Simultaneity	Program Plan - technology too new	Req Standards	Tech component slip causes everything to slip	Security Reqts	KPP performance goal	Systems Design	Antenna tracking	Contractor Program management	ACAT status	Acquisition contracting	Eng Change Propsal delay	Contractor Performance	Increment 2	Award Fee	Contractor/PO Relationship	Project Dev Env	Satellite Simulation	Schedule delay event	Certifications
Acquisition policy		0	0	0	0	0	0	0	0	0	0	2	0	1	1	0	0	0	3	1	0	0	0	1	0	0	0	1	0
Change in Strategic Vision	1		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0
Mission / CONOPS	0	0		2	2	2	3	2	0	2	0	0	1	1	3	1	2	0	1	0	0	0	0	0	0	0	2	0	0
Interdependency Program A	0	0	0		0	0	3	0	3	3	0	0	0	0	2	1	3	0	0	0	0	2	0	0	0	0	0	2	0
Interdependency program B	0	0	0	0		0	3	0	3	0	0	0	0	0	2	1	0	0	0	0	0	2	0	0	0	0	2	2	0
Interdependency Program C	0	0	0	0	0		3	0	3	2	2	0	0	0	2	1	0	0	0	0	0	2	0	0	0	0	0	2	0
KPP selection	0	0	0	0	0	0		0	0	0	1	0	0	0	3	2	0	0	0	0	0	1	1	0	1	0	2	0	0
Interdependency Agency D	0	0	0	0	0	0	0		3	0	0	0	0	3	0	1	0	0	0	0	0	2	0	0	0	0	0	2	2
Waveform (new tech)	0	0	0	0	0	0	0	0		2	3	0	2	1	2	2	2	0	0	0	3	0	1	0	0	0	3	1	0
Signal Simultaneity	0	0	0	0	0	0	0	0	0		2	0	0	8	0	2	1	0	1	0	0	0	2	0	0	0	2	0	0
Program Plan - technology too new	0	0	0	0	0	0	0	1	1	1		1	1	1	0	3	3	0	1	1	3	1	1	1	1	1	1	0	0
Reqt Standards	0	0	0	0	0	0	0	0	0	0	0		0	0	1	1	0	0	0	0	0	1	1	0	0	0	2	0	3
Tech component slip causes everything to	0	0	0	0	0	0	0	0	0	0	0	0		3	0	0	0	0	0	0	0	0	3	0	0	0	1	3	0
Security Reqts	0	0	0	0	0	0	1	0	0	0	0	2	0		0	1	1	0	0	0	0	0	1	0	0	1	1	2	0
KPP performance goal	0	0	0	0	0	0	0	0	0	0	0	0	1	0		3	3	0	0	0	0	0	0	0	0	0	0	0	0
Systems Design	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0		2	0	0	0	0	0	2	0	0	0	2	0	1
Antenna tracking	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2		0	1	0	2	0	2	0	0	0	2	0	0
Contractor Program management	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0		0	0	2	3	0	2	2	3	0	1	0
ACAT status	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2		3	0	2	0	0	1	0	0	0	0
Acquisition contracting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0		3	2	0	2	2	0	0	1	0
Eng Change Propsal delay	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0		2	0	2	1	1	0	3	0
Contractor Performance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	1	0		0	3	3	2	0	0	0
Increment 2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0		0	0	0	0	2	0
Award Fee	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0		2	0	0	0	0
Contractor/PO Relationship	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2	0	2		2	0	0	0
Project Social / Dev Env	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1		0	0	0
Satellite Simulation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2		1	0
Schedule delay event	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0		0
Certifications	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	

Figure 2. Example Dependency Matrix After DSM Transofrmation

Construct a Bayesian Belief Network

A BBN is constructed using the program change drivers derived from the expert workshop and their cause-and-effect relationships. The BBN models the change drivers as nodes in a quantitative network and includes the conditional probabilities that changes of state in one node will create a change of state in another node, as envisioned by the program domain experts. Figure 3 depicts an abbreviated visualization of a BBN, with circled nodes representing program change drivers and arrows representing either cause-and-effect relationships or leading indicator relationships. This example shows that a change in the Mission & CONOPS driver will likely cause a change to the Capability Analysis driver, which in turn will likely change the Key Performance Parameters (KPPs) driver and subsequently the Technical Challenge outcome factor. The three outcome factors (Product Challenge, Project Challenge, and Size Growth) and their corresponding states are mapped to some of the traditional cost model input factors and their values.

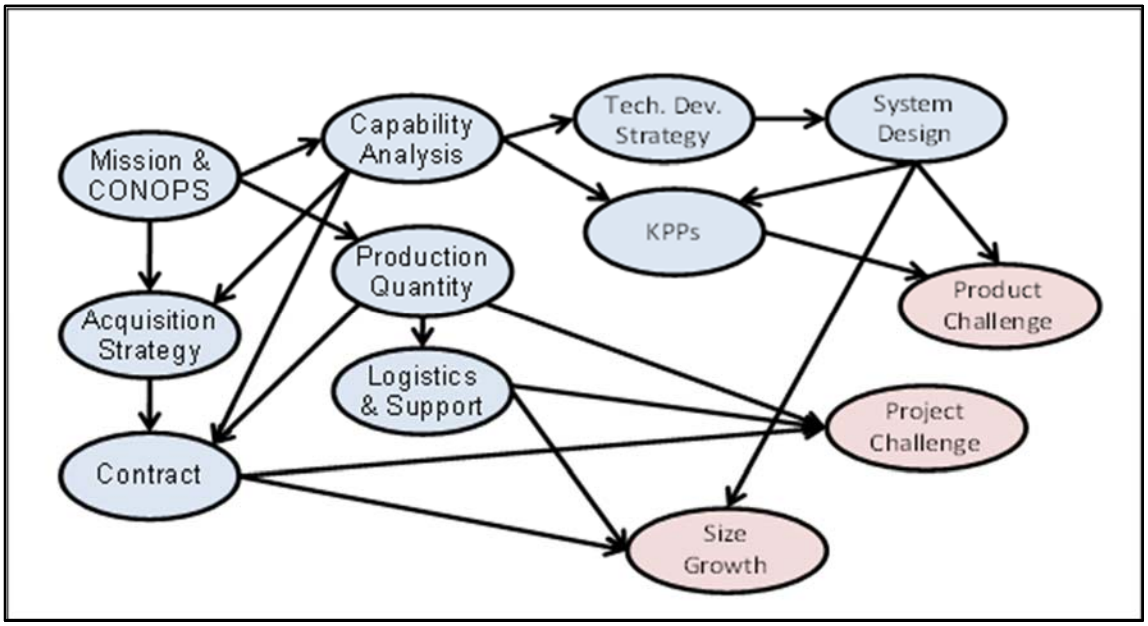


Figure 3. Example BBN

Conditional probabilities are assigned to the nodes (drivers) in the BBN. Each node can assume a variety of states with an associated likelihood identified by the domain experts. This allows the calculation of outcome distributions on the variables.

Domain experts use the BBN to define scenarios. The realization of a potential state in a particular node is specified, and the cascading impacts to other nodes and the resulting change in the outcome variables are recalculated. Any change in one or more nodes (drivers) constitutes a scenario. Once the experts are satisfied that a sufficient number of scenarios are specified, they use their judgment to rank them for likely impacts to cost. An example scenario created during an SEI pilot workshop is provided in Figure 4.

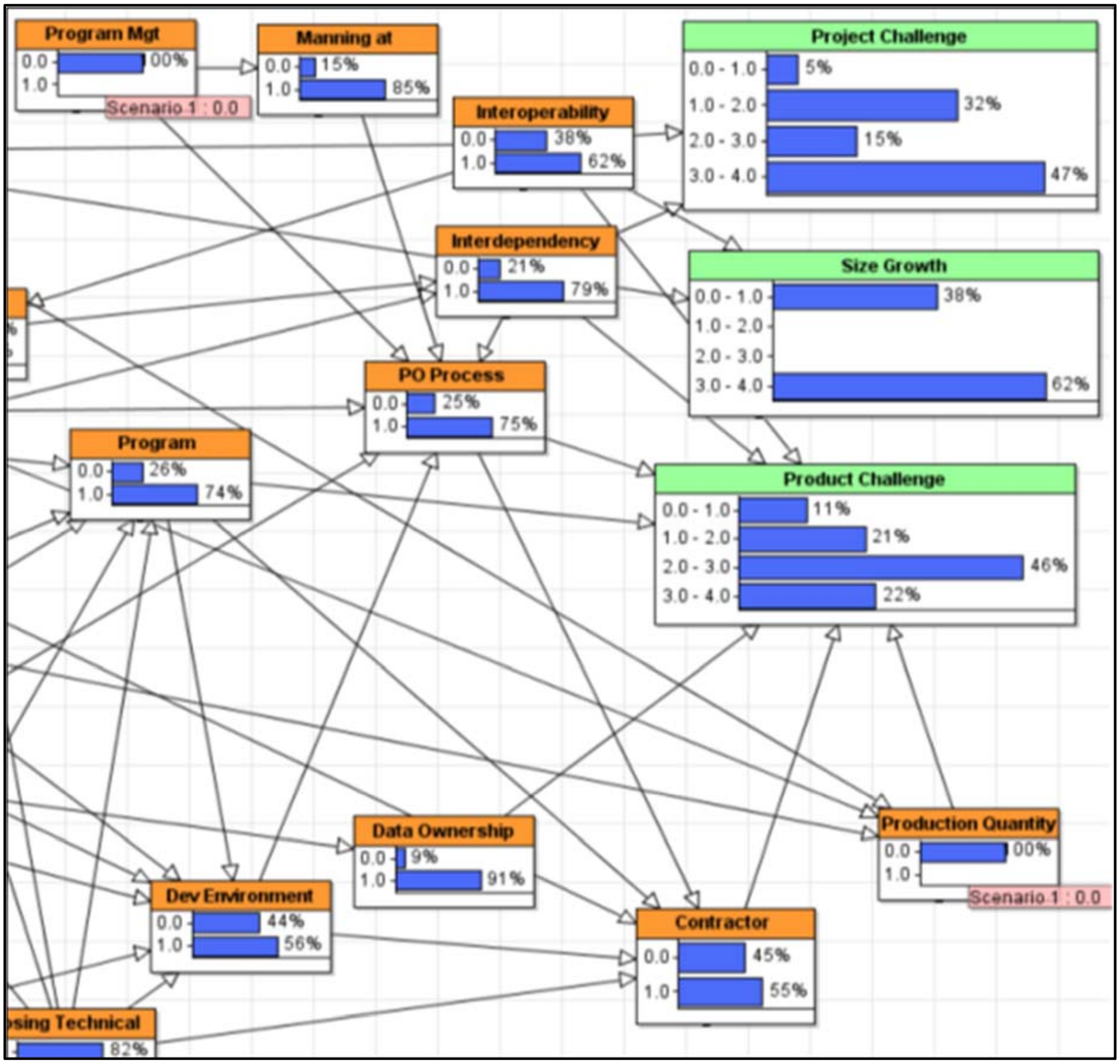


Figure 4. A Partial Example of a Scenario With Two Driver Nodes in a Nominal State

Select Cost Estimating Models to Generate an Estimate

Parametric cost estimation models for software use a mathematical equation to calculate effort and schedule from estimates of size and a number of parameters. A decision is made as to which cost estimating tools, cost estimating relationships (CERs), or other methods will be used to form the cost estimate. COCOMO II is a well-known estimation tool and is open source. The SEI has so far developed the relationships between BBN-modeled program change drivers and COCOMO, shown in Figure 5. The red X's in brackets indicate an inverse relationship between the BBN output factor and the corresponding COCOMO II driver. The black X's indicate a positive relationship. The BBN interface to the commercial SEER-SEM cost estimating tool is currently underway.

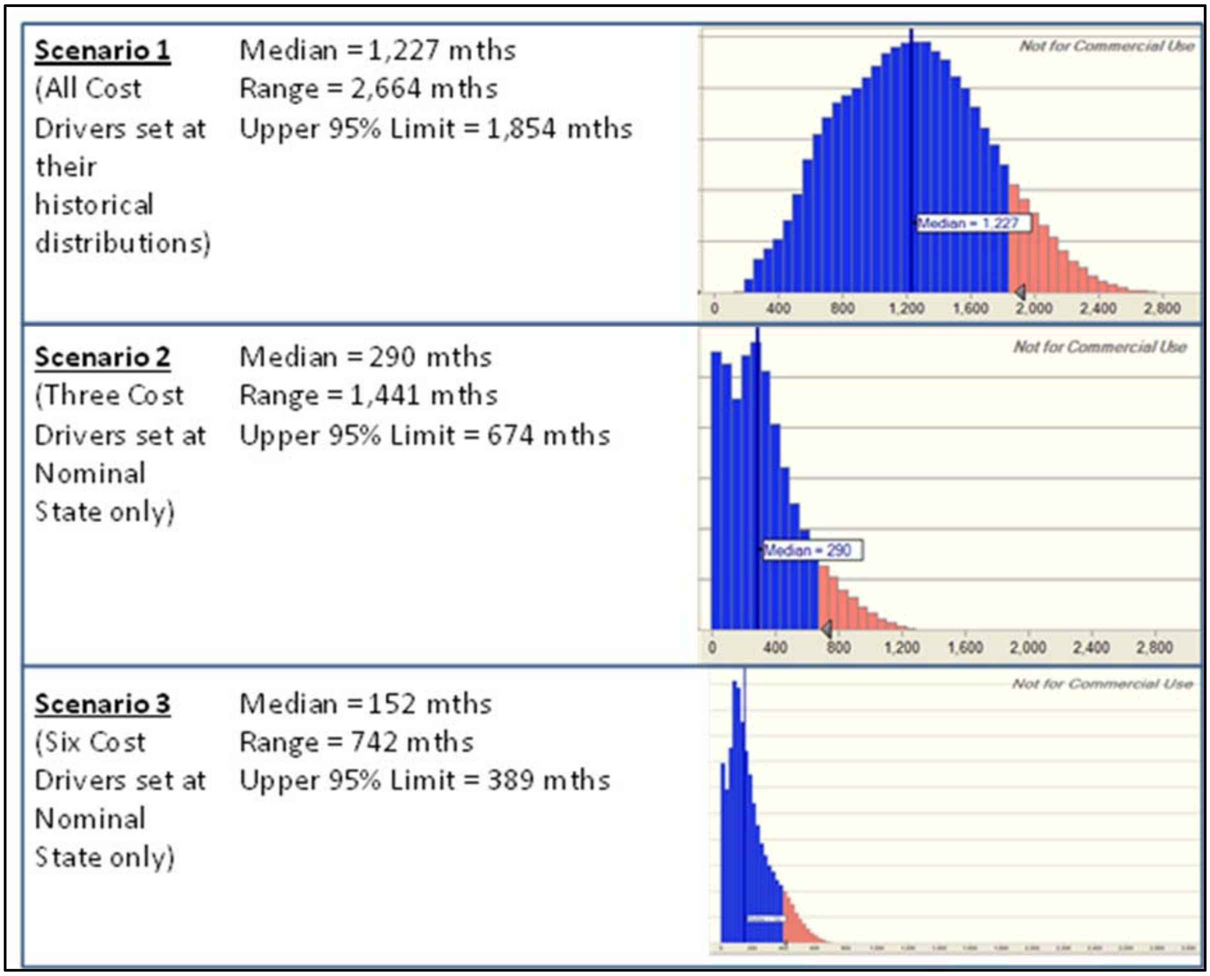
Drivers	**XL**	**VL**	**L**	**N**	**H**	**VH**	**XH**	**Product**	**Project**
Scale Factors									
PREC		6.20	4.96	3.72	2.48	1.24	0.00	**<X>**	
FLEX		5.07	4.05	3.04	2.03	1.01	0.00	**<X>**	
RESL		7.07	5.65	4.24	2.83	1.41	0.00	**<X>**	
TEAM		5.48	4.38	3.29	2.19	1.10	0.00		**<X>**
PMAT		7.80	6.24	4.68	3.12	1.56	0.00		**<X>**
Effort Multipliers									
RCPX	0.49	0.60	0.83	1.00	1.33	1.91	2.72	**X**	
RUSE			0.95	1.00	1.07	1.15	1.24	**X**	
PDIF			0.87	1.00	1.29	1.81	2.61	**X**	
PERS	2.12	1.62	1.26	1.00	0.83	0.63	0.50	**<X>**	
PREX	1.59	1.33	1.12	1.00	0.87	0.74	0.62		**<X>**
FCIL	1.43	1.30	1.10	1.00	0.87	0.73	0.62		**<X>**
SCED		1.43	1.14	1.00	1.00	1.00			**<X>**

Figure 5. Mapping BBN Outputs to COCOMO Inputs

The program office estimates of size and other cost model inputs such as productivity are used as the starting point in this step. Often these values are estimated by analogy and aggregation. They are adjusted by applying the distributions calculated by the BBN.

Monte Carlo Simulation

From each selected scenario, we use the output of the BBN to parameterize a Monte Carlo simulation of the inputs to the selected cost estimation model. This provides probability distributions for the input factors to the cost estimating models. This also provides explicit confidence levels for the results. Figure 6 shows the simulation results that the SEI obtained when modeling a factor (person-months) in three different scenarios.



Scenario 1 (All Cost Drivers set at their historical distributions)
Median = 1,227 mths
Range = 2,664 mths
Upper 95% Limit = 1,854 mths

Scenario 2 (Three Cost Drivers set at Nominal State only)
Median = 290 mths
Range = 1,441 mths
Upper 95% Limit = 674 mths

Scenario 3 (Six Cost Drivers set at Nominal State only)
Median = 152 mths
Range = 742 mths
Upper 95% Limit = 389 mths

Figure 6. Simulation Results for Three Scenarios

A report with the final cost estimates is generated for each scenario, including the nominal (expected) program plan. The explicit confidence levels and the visibility of all considered program change drivers allow for quick comparisons and future re-calculations. This method enables the creation of comparative scenario calculations at any point during the life cycle. The visibility of the program change drivers and the transparency afforded by the consideration of alternative scenarios—and their assumptions—enables improved decision-making and contingency planning.

Results and Future Research

To date, there have been two empirical thrusts to the research. First, we have conducted a retrospective on an MDAP. We constructed a 10-year time line of the program using archival documents, records from various DoD repositories, and collaborations with SEI staff who worked on the program.

The team accessed over 4,100 program files, which documented virtually all of the program's history. In addition, the team obtained over 100 official contractor submissions of Software Resource Data Reports (SRDRs) and Earned Value Management Reports contained in the Defense Automated Cost Information System. We also obtained acquisition reports from the Defense Acquisition Management Information Retrieval (DAMIR) Purview repository, which included the relevant Selected Acquisition Reports (SARs) and the Defense Acquisition Executive Summary (DAES) Reports.

With the participation of two in-house experts who had worked with the program, we established a provisional set of 57 program-specific change drivers. We also elicited their judgment on the likelihood of change for each of the program change drivers and their potential cascading effect on the other drivers. These judgments formed the basis for implementing DSM techniques to reduce the complexity and capture the cascading effects of the interdependencies among the program change drivers.

DSM reduced the number of program change drivers to those that the experts considered to have moderate or high likelihood of change during program execution. While the matrix manipulation techniques will often remove many of the cycles in the matrix, expert judgment is also required to eliminate cycles that are not removed by the algorithms and rating criteria. In the context of this retrospective, we also realized that asking the experts to mentally reconstruct what potential changes might have been considered at the early stages of the program did not avoid problems in bias based on later experience. But if implemented at pre–Milestone A as envisioned, these judgments represent the reality of the early life cycle estimation process. In the end, we were left with 30 program change drivers that formed the acyclic graph required for the construction of the BBN.

In assigning the required conditional probabilities for the BBN to each change driver, we utilized both the experts' elicited judgments of probability and the ranges of variance produced from the expert calibration experiments performed earlier. The elicited probabilities were used to directly populate some portions of the BBN. However, we quickly realized that it was not feasible to elicit all of the probabilities and conditional probabilities required for such a complex BBN. Hence, we adapted an algorithmic approach to specifying the needed probabilities. To represent the uncertainty in the elicited probabilities and to incorporate this into the computed probabilities, we used the second element noted earlier, the ranges of variance produced by experiments conducted to calibrate expert judgment to a 90% confidence range. This calibration research is the second thrust of this work and is documented in a separate technical report (Goldenson & Stoddard, 2013).

For purposes of demonstration, we relied on using the results of those experiments. However, in a "live action" MDAP, we would use the actual program experts' calibration results, which would be obtained through a calibration test. The technical workshop with the MDAP experts would then serve to both elicit their required judgments as described earlier and allow them to participate in a series of calibration training exercises. The exercises sharpen expert abilities to exert less overconfident and less overoptimistic judgment while also producing the required data for us to capture uncertainty within the BBN.

The resulting retrospective BBN enabled the output of probability distributions used as inputs to the cost estimation tool. We constructed linkages to the SEER-SEM cost estimation tool used by the program for the system software components comprising it. Monte Carlo techniques allowed us to generate confidence intervals for these distributions, which were then used for input to the cost model.

We are close to completing the retrospective and will be comparing the results of the QUELCE model with the estimates and actual costs produced by the program. The conduct of the retrospective helped us refine our elicitation approach, demonstrated the complexity of populating a BBN at scale, and illuminated the need for calibrating teams of experts, not just individuals. Remaining work involves obtaining a review of our decisions about connecting the BBN to cost models such as COCOMO and SEER.

Conclusion

Extensive cost overruns have been endemic in defense programs for many years. A significant part of the problem is that the information used for cost estimates of unprecedented systems must rely heavily on expert judgments. When done early in the system's life cycle, the estimate is based only on the concept and incorporates much uncertainty as to how that concept will be developed into a fully deployed operational system. QUELCE aims to reduce the adverse effects of that uncertainty. Important program change drivers and the dependencies among them that may not otherwise be considered in forming estimates are made explicit to improve their realism and accuracy. The basis of an estimate is documented explicitly, which facilitates updating the estimate during program execution and helps others to make informed judgments about their accuracy. Variations in the range of possible states of the program change drivers that may occur under different likely scenarios are explicitly considered. The use of probabilistic methods combining Bayesian belief systems and Monte Carlo simulation will ultimately place the cost estimates within a more realistic range of uncertainty.

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