

THE ESTIMATE AT COMPLETION PROBLEM: A REVIEW OF THREE STUDIES¹

INTRODUCTION

On 7 January 1991, Secretary of Defense Cheney canceled the Navy's A-12 Avenger Program. The A-12 Avenger, an advanced attack aircraft in full-scale development, was the Navy's premier aviation project of the 1980s. Although there were many reasons for the cancellation, certainly the problem of estimating its completed cost was an important contributing factor. At the time of its cancellation, the projected completion cost, termed the "Estimate at Completion" (EAC), was estimated at \$1 billion over the contract ceiling. This estimate differed significantly from other estimates supported by the A-12 Program Office and by the contractors. Although the A-12 cancellation increased interest in the EAC, basic uncertainties regarding its computation continue. This article reviews EAC formulas and several studies that examine their accuracy. Examples from the A-12 Program are used to illustrate key issues. Generalizations and suggestions conclude the article.

EAC FORMULAS

The EAC can be computed by formula using cost management data provided by the contractor to the government in the *Cost Performance Report* or the *Cost/Schedule Status Report*. The reliability of these reports depends on the degree to which the contractor adheres to a strong system of internal controls involving the scheduling, budgeting, costing, and analysis of contractual effort [9]. In the A-12 Program, contractor compliance to these controls, known as "Cost/Schedule Control System Criteria," was judged satisfactory by the cognizant contract administration offices. Therefore, the cost data provided by the A-12 contractors were suitable for independent EAC calculations.

All EAC formulas are based on the combination of several data elements presented on the cost management report: ACWP, BCWS, and BCWP. The Actual Cost of Work Performed (ACWP) is the cost of the work as it is accomplished on the contract. The Budgeted Cost of Work Scheduled (BCWS) is the time-phased budget for all the contractual effort. At any time on the contract, it represents the budget for work that is planned to be accomplished by that time. Accordingly, BCWS is also termed "planned value." The Budgeted Cost of Work Performed (BCWP) is the same number as BCWS, but is recorded as work is actually accomplished or earned. BCWP is also known as "earned value."

Figure 1 illustrates the relationship between these three data elements, and is typical of most defense acquisition contracts: behind schedule and over budget. Because the actual cost of the completed work (ACWP) exceeds the budget for the completed work (BCWP), the contract is over budget. Because the amount of work actually accomplished (BCWP) is less than the amount of work that was planned to be accomplished (BCWS), the contract is behind schedule.

The figure also illustrates other key data elements reported by the contractor: BAC and EAC. The Budget at Completion (BAC) is the total budget for all of the known work on the contract. The Estimate at Completion (EAC) is the projected completion cost. As shown, the EAC is the actual cost of the completed work plus the budget for the remaining work.

The generic formula for the EAC is as follows:

$$EAC = \frac{ACWP_c + (BAC - BCWP_c)}{Index} \quad (1)$$

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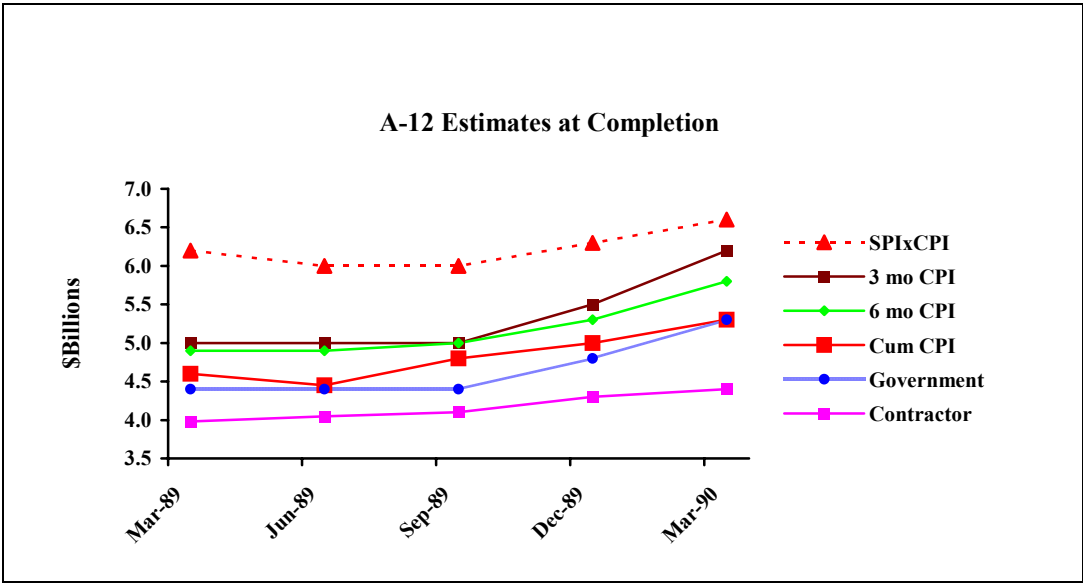


Figure 2. EACs for A12 Program [1].

The subscript “c” indicates cumulative data. Because actual costs typically overrun the budget on defense contracts, the budget of the remaining work ($BAC - BCWP_c$) requires an upward adjustment. A performance factor is used to make this adjustment, and is normally a measurement of past cost or schedule performance on the contract, termed a “performance index.” The assumption implicit in this adjustment is that the contract’s past cost and schedule performance is reflective of future performance. Research has confirmed the reasonableness of this assumption [3].

These “performance indices” are classified into four groups:

$$\text{Cost Performance Index (CPI)} = BCWP/ACWP \quad (2)$$

$$\text{Schedule Performance Index (SPI)} = BCWP/BCWS \quad (3)$$

$$\text{Schedule Cost Index (SCI)} = SPI \times CPI \quad (4)$$

$$\text{Composite Index} = w_1 \times SPI + w_2 \times CPI \quad (5)$$

The weights shown in Equation 5 (w_1 and w_2) can take on any value from 0 to 1, and normally add to unity. These indices can be based on monthly, cumulative, or averaged data. Usually, the average index is defined as a ratio of sums through x months.

$$CPI_x = \Sigma BCWP_x / \Sigma ACWP_x \quad (6)$$

$$SPI_x = \Sigma BCWP_x / \Sigma BCWS_x \quad (7)$$

An alternative definition is to divide the sum of monthly indices by the appropriate number of months:

$$CPI_x = \sum_{i=m-\lambda+1}^m CPI_i / X \quad (8)$$

$$SPI_x = \sum_{i=m-\lambda+1}^m SPI_i / X \quad (9)$$

For this article, the following labeling conventions are adopted: “ CPI_m ” represents a CPI based on the most recent month; “ CPI_c ” represents a cumulative CPI; “ CPI_x ” represents a CPI averaged over x number of months, beginning with the most recent month and going backwards. For example, CPI_3 represents a three-month average CPI, with the current and last two previous months included. SPI and SCI use the same conventions.

As defined above, when the performance index is less than 1, an unfavorable condition exists. For example, in an overrun condition the CPI is less than 1 because the actual cost of the completed work exceeds the budgeted cost of completed work. Similarly, in a behind schedule condition SPI is less than 1 because less work has been accomplished than was planned to be accomplished by a certain date.

These indices may be computed for any element of work on the contract, or the entire contract. Because defense contracts are usually over-budget and behind schedule, the CPI and SPI are usually less than 1. Dividing the CPI, SPI, or any combination of them into the budget of work remaining on the contract will therefore increase the EAC of that contract. The degree of the increase depends on the specific index, and on the number of months included in the index.

In the A-12 Program, the program manager relied on the EAC computed using the cumulative CPI despite several higher estimates briefed to the Program Office. As shown in Figure 2, this number was only slightly

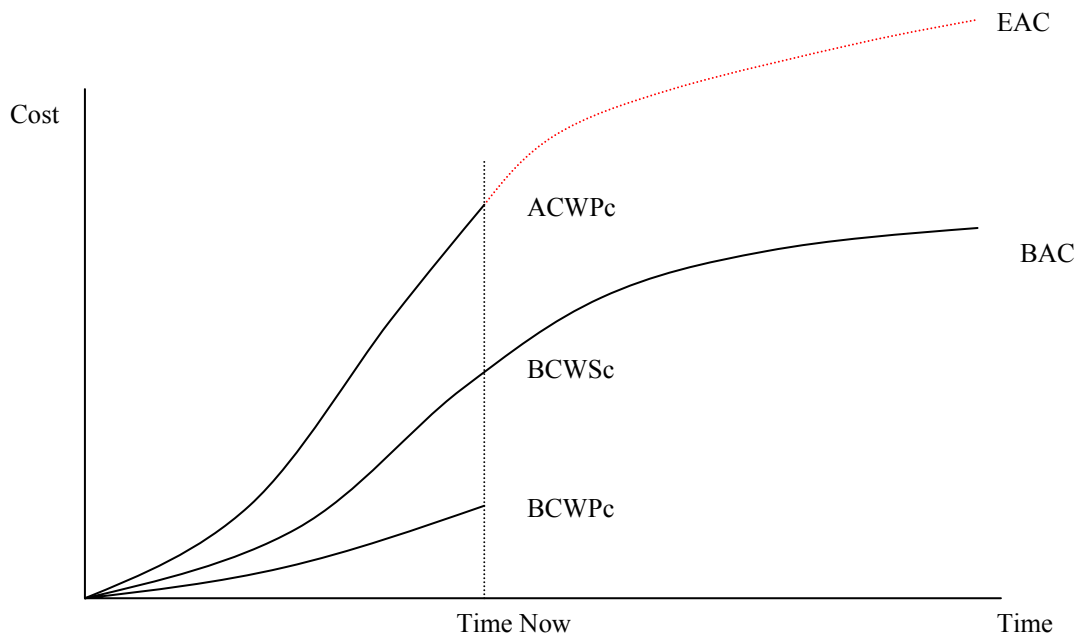


Figure 1. The Estimate At Completion (EAC).

larger than the contractor's EAC. When the EAC was computed using indices averaged over shorter time periods (i.e., three months, six months), the number was considerably larger. The largest EAC in Figure 2 is computed using the SCI_c . Because SPI and CPI are usually less than 1, their product (SCI) is smaller than either. Therefore, when the SCI is divided into the budget for work remaining, the result is a large EAC.

Exactly why the A-12 Program Office chose to support such an optimistic EAC is unclear. The Navy Inquiry Officer, Chester P. Beach, suggested that "abiding cultural problems" effectively suppressed pessimistic information [1]. The program manager denied that pessimistic data were suppressed. In any case, the problem of choosing the appropriate EAC formula or group of formulas remains.

Beach also stated that the CPI_c is a reasonable floor for a reasonable range of EACs [1:6-7]. This is because the CPI_c does not usually change by more than 0.10 once the contract is 20 percent complete; in most cases, it tends to decrease [3]. Therefore, using non-cumulative indices averaged over shorter time periods will likely result in larger EACs.

Other EAC formulas are based on regression analysis, time-series analysis, or complicated heuristics. Formulas of this kind have not been as popular as index-based formulas because they demand a familiarity with sophisticated statistical methods. The regression-based formulas are typically derived using linear or nonlinear univariate regression analysis, where ACWP is assumed to be a function of BCWP. Once the regression model's coefficients are determined, the total budget for the known work, BAC, is substituted for BCWP to compute the EAC. A review of these more complicated EAC formulas and related studies is presented elsewhere. [4].

It is apparent that there are an infinite number of possible EAC formulas. The analyst is left with the potentially frustrating task of deciding which formula or group of formulas to use. *Performance Analyzer* [14], software widely used in the DOD to analyze cost management reports, allows the user to choose from a variety of formulas. However, no guidance is provided regarding which formula or group of formulas is most accurate.

The government program manager is now required to provide a range of EACs, reflecting best and worst cases, to the Office of the Undersecretary of Defense. If the EAC supported by the contractor is below the range of EACs computed by selected formulas, the government may wish to challenge the contractor's number. Additionally, if the program manager's "best estimate" is below the EAC computed using CPI_c , then specific justification must be provided [8].

The next part of this article will address the issue of which formulas to use by reviewing three studies that have compared the accuracy of EAC formulas. The scope and results of each study are briefly described.

EAC STUDIES

EAC studies compare the predictive accuracy of two or more EAC formulas. The general approach is to collect data on completed or nearly completed contracts, compute EACs using various formulas, and compare each to the reported Cost at Completion (CAC). The EAC formula that provides the smallest percentage deviation from the CAC is defined as the most accurate.

In the past 30 years, there have been over 25 EAC studies [4]. Most of these have been thesis or special studies sponsored by the Army, Navy, or Air Force, and have never been published. Only three of these are reported here. Generally, these three were the most comprehensive and thorough of the ones reviewed. They adjusted the data for problems created by scope and baseline changes, and evaluated formula accuracy by stage of completion, the type of weapon system, and the type of contract (production or development).

The scope of the three studies is summarized in Table 1 by author, year, service (Army, Navy, Air Force), number of contracts, and types of EAC formulas (index-based, regression-based). There are four categories of index-based formulas (CPI , SPI , SCI , and Composite) and two categories of regression-based formulas

(linear, nonlinear). For CPI, SPI and SCI, the period through which the index is averaged (1 month, 3 months, 6 months, 12 months, cumulative, and other) is listed. For the composite index, the weight assigned to SPI is listed first. For example, “20/80” means a 20 percent weight to SPI and an 80 percent weight to the CPI. An “X” in the table indicates the EAC formula was included in the study. For example, Reidel and Chance [13] compared the accuracy of the one-month CPI, the cumulative CPI, the cumulative SCI, and two kinds of composite indices.

The results of each study are provided next.

Covach, Haydon, and Reither [5] (for Navy Weapons Engineering Support Activity) evaluated 12 index-based formulas and 12 regression-based models using data from 17 contracts (14 development, 3 production) managed by the Navy. The indices were computed using single, averaged, and cumulative data. Average CPIs were based on 3, 6, and 12 month periods. Other CPIs involved dividing an average CPI into BAC. Two other index-based formulas were SPI_c and an inaccurate use of the SPI, where SPI_c is divided into BAC. Twelve regression-based models were evaluated, using $ACWP_c$, $BCWP_c$, or CPI_c as the dependent variable, and $BCWP_c$ or time (months) as the independent variable. For each regression, four curvilinear relationships were tested. Unfortunately, the index-based formulas were not compared to the regression-based models.

A summary of the results from comparing index-based formulas is provided in Table 2. Average CPIs defined by Equation 6 were generally more accurate than those defined by Equation 8. The equations which involved dividing an average index into BAC were completely discredited (as they should be).

Results of comparing the regression-based models were less clear. No one model always performed well. Once a model began to perform well, it usually continued to be the best regression-based model.

Finally, for all of the formulas and models evaluated, EACs computed from level one data in the work breakdown structure were as accurate as EACs computed at lower levels and summed to level one.

Bright and Howard [2] evaluated 11 formulas and models using data from 11 development contracts managed by the Army. Nine index-based formulas (CPI_3 , CPI_6 , CPI_{12} , CPI_c , SPI_c , SCI_c , SPI_x , CPI_6 , $0.5CPI_c + 0.5SPI_c$, $0.75CPI_c + 0.25SPI_c$) and two regression-based models (one linear, one nonlinear), with $ACWP$ regressed against CPI , were evaluated at various contract stages.

Results are summarized in Table 3. In the early stage, Bright and Howard concluded that the two regression-based models performed better than the formulas. Of the formulas, the composite indices were the most accurate. The information content of the SPI was shown to decrease, as composite formulas giving larger weights to SPI were more accurate in the early stages of the contracts examined. In the middle stages, the averaged CPIs were most accurate. Bright and Howard suggested that when contracts have significant cost variance growth in the middle stages, an index averaged over a shorter period is more accurate than one averaged over a longer period. In the later stages, CPI_c and SCI were most accurate. The SCI was also found to be a reasonably accurate index in the early stages of the contracts examined. Of various combinations of SCI s, examined, $SPI_c \times CPI_6$ was the most accurate.

Reidel and Chance [13] evaluated six index-based formulas using data from 56 contracts (16 development, 40 production) managed by the Air Force. The six formulas (CPI_m , CPI_3 , CPI_c , SCI_c , $0.2SPI_c + 0.8CPI_c$, and $(X)CPI_c + (1-X)SPI_c$, where X = percent complete) were evaluated at four completion stages (25%, 50%, 75%, 100%). The sensitivity of the results to the type of weapon system (8 aircraft, 3 avionics, and 5 engines) was also evaluated. Generally, EACs for production contracts were more accurate than EACs for development contracts. More specific results are summarized in Table 4. The term “PC” stands for the formula using percent complete to adjust the weights in the composite index. The term “20/80” stands for a 20 percent weight on the SPI_c and a 80 percent weight on the CPI_c of the composite index.

TABLE 1

EAC FORMULAS AND MODELS EXAMINED IN THREE EAC STUDIES

Authors (Year, Service)	Contract		CPI†						SPI‡		SCI‡		Composite‡			Regression‡	
	Development	Prod	1	3	6	12	Cum	Other	Cum	Other	Cum	Other	20/80	50/50	Other	L	NL
Covach, Haydon, Reither (1981, Navy)	14	3	X	X	X	X	X	X		X	X					X	X
Bright, Howard (1981, Army)	11			X	X	X	X		X		X	X		X	X	X	X
Riedel, Chance (1989, Air Force)	16	40	X				X				X		X		X		

† The numbers in the column under “Contract” indicate the number of development and production contracts included in each study. For example, Riedel and Chance included 16 development and 40 production contracts in their study.

‡ The remaining columns indicate the four types of index-based formulas) CPI, SPI, SCI, Composite) and two types of regression models (linear and nonlinear) that were compared in the three studies. An “X” indicates the EAC formulas and models include in each study. For example, Riedel and Chance examined the accuracy of the 1-month CPI, the cumulative SCI, and two kinds of composite indices.

GENERALIZATIONS

The larger and more diverse the number of contracts used in an EAC study, the more compelling the results. As shown in Table 1, the Reidel and Chance [13] study was easily the largest and most diverse, with 56 contracts. However, all of these contracts were managed by the Air Force. Generalizing the results of the Air Force study to contracts managed by the Army or Navy is suspect because each Service may differ on the nature and degree of oversight afforded a contractor's management control systems and database. With this caveat, the following generalizations are provided.

The accuracy of regression-based models over index-based formulas has not been established.

Most of the early research in EAC forecasting involved nonlinear regression or time series analysis, showed promise, but suffered from small sample sizes. Studies with larger sample sizes had mixed results. Bright and Howard [2] showed a regression model to be more accurate than selected index-based formulas in the early stages, but suggested that using the model was not popular because management would not support early, pessimistic forecasts, however accurate! Despite their comment, with the wide availability and decreased cost of computer technology and statistical software, additional research exploring the potential of regression and time series analysis to forecast the EAC is badly needed.

The accuracy of index-based formulas depends on the type of system, and the stage and phase of the contract.

As detailed in Tables 2, 3, and 4, no one formula is always best. Assigning a greater weight to the SPI early in the contract is appropriate. Because the SPI is driven to unity, it loses its predictive value as the contract progresses. SCI-based formulas were shown to be better predictors in the early stages in all three studies. In the late stages, SCI_c and CPI_c have nearly the same values, and were shown to be accurate predictors by Bright and Howard [2] and Riedel and Chance [13].

The long-asserted [15] accuracy of the composite index with a 20/80 percent weighting on SPI and CPI, respectively, is not supported by the evidence. Riedel and Chance [13] document the accuracy on this composite index on only a small subset of the contracts. Accordingly, the arbitrary use of this weighting should be avoided. There is no substitute for familiarity with the contract.

Averaging over shorter periods (e.g., 3 months) is more accurate than averaging over longer periods (e.g., 6-12 months), especially during the middle stages of a contract when costs are often accelerating [2] [5] [13]. In addition, computing the average as the "ratio of sums" (Equations 6, 7) rather than as the "average of monthly indices" (Equations 8, 9) results in slightly more accurate forecasts [5].

CONCLUSION

It is hoped that this selected review of comparative EAC research will be of value to analysts and managers involved with EAC forecasting. The use of *Performance Analyzer* or other analysis software has reduced the mathematical burden of developing independent EACs, but it is no substitute for the experienced judgment of analysts and managers.

But this judgment must not be impaired by a culture that suppresses truth. The EAC problem runs much deeper than selecting the most accurate formulas. When Secretary Cheney canceled the A-12 Program, he complained that no one could tell him how much it would cost to keep it going [12]. In fact, there were many estimates of its cost. Most of these were much more pessimistic than the one supported by the Program Office. Beach [1] reported that the A-12 program manager chose to rely on a lower estimate, despite several higher ones presented by his own analyst, and suggested that "abiding cultural problems" effectively suppressed the more pessimistic estimates. Navy Secretary Garret voiced a similar concern in testimony to the House Armed Services Committee [10], when he characterized senior program office professionals as "can do" people who do not admit to failure easily. In short, a "shoot-the-messenger"

TABLE 2

**RESULTS OF EAC COMPARISONS [5]
(14 Development and 13 Production Navy Contracts)**

<i>Completion Stage</i>	<i>Best Performing Index</i>
Early (0% - 40%)	CPI ₃ , CPI _c , SCI _c
Middle (20% - 80%)	CPI ₃ , CPI ₆ , CPI _c , SCI _c
Late (60% - 100%)	CPI ₃ , CPI ₆ , CPI ₁₂

TABLE 3

**RESULTS OF EAC COMPARISON [2]
(11 Development Army Contracts)**

<i>Completion Stage</i>	<i>Best Performing Formula/Model</i>
Early (0% - 40%)	Regression, Composite, SPI _c , SCI
Middle (20% - 80%)	CPI ₃ , CPI ₆ , CPI ₁₂
Late (60% - 100%)	CPI _c , SCI

TABLE 4

**RESULTS OF EAC COMPARISONS [13]
(16 Development and 40 Air Force Production Contracts)**

<i>Phase</i>	<i>System</i>	<i>Completion Stage</i>				<i>Overall</i>
		<i>25%</i>	<i>50%</i>	<i>75%</i>	<i>100%</i>	
Development	Aircraft	SCI _c	CPI ₃	CPI ₃	20/80	SCI _c
Production	Aircraft	SCI _c	CPI ₃	SCI _c	CPI ₃	SCI _c
Development	Avionics	SCI _c	CPI ₃	SCI _c	CPI ₃	CPI ₃
Production	Avionics	20/80	SCI _c	20/80	SCI _c	20/80
Development	Engine	CPI _m	SCI _c	CPI ₃	CPI ₃	CPI ₃
Production	Engine	PC	CPI _c	SCI _c	PC	CPI _c

culture will absolutely destroy responsible decision making by biasing the database or the analyst of it. Until this problem is resolved, the accuracy of EAC formulas is of secondary importance.

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