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Realistic Acquisition Schedule Estimates: A Follow-On Inquiry

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Abstract

In a 2016 proceedings paper for this symposium (Franck, Hildebrandt, & Udis, 2016), we outlined and discussed a research agenda with an aim of more realistic acquisition program scheduling estimates, especially for the development (SSD) phase. This paper is intended to continue pursuit of that agenda, with the aim of demonstrating its feasibility and discussing methods of analysis. Accordingly, this paper is presented in four parts: the promise of Systems Dynamics as a schedule-estimating paradigm; a preliminary case study of cost-performance-schedule tradeoffs in the F-35 program; the development of measures of effectiveness for contemporary air-to-air combat; and finally an examination of data sources and empirical models for program and contract schedule uncertainty.

Introduction

Among other things, our proceedings paper for the 13th Annual Acquisition Research Symposium proposed a research agenda intended to enable more realistic acquisition schedule estimates (Franck et al., 2016). This paper pursues that agenda along a number of lines—with the aim of finding or exercising methodologies that can be applied to developing more realistic schedule estimates.

Program schedule time could possibly be analyzed and forecast according to the following menu (p. 99):

- An orderly function involving key variables. This would lead to “schedule estimating relationships.”

- A result of a series of management decisions intended to produce the best program. At the macro level, this is a set of cost-performance-schedule tradeoffs, which are related in complex, imperfectly understood ways.
- An outcome result arising from the interactions among a set of tasks needed to complete the program. Among other things, this raises the question of tracing through the sometimes tangled relationships among various parts of the program (perhaps unplanned).

In that vein, we've undertaken to explore methods to better understand all three approaches.

We explore ways to identify the key variables for estimating schedule length—with a view to developing "schedule estimating relationships." In the first section, Pickar offers an overview of Systems Dynamics methodology in understanding the evolution of acquisition programs over time. Ability to model events and processes has potential to provide insights into the effects of decisions and unplanned events on acquisition timelines.

Another way of better understanding those decisions, unplanned events, and their outcomes is through case studies. In the next section, Franck and Udis undertake a preliminary case study of the F-35—with a focus on system tradeoffs.

In the section titled Better Understanding Acquisition Schedules Through Better Performance Measures, Franck assumes that system performance is a promising variable for schedule estimating relationships, and essays a preliminary approach to performance measurements for contemporary air combat systems—beginning with variants of Lanchester models of combat. This section also suggests that improved methods of performance quantification can shed light on cost-performance-schedule tradeoffs (the macro-level tasks of program management).

Finally, in the Program and Contract Schedule Uncertainty section, Hildebrandt undertakes continued study of schedules, and variances thereto, using statistical and econometric approaches with particular emphasis on data sources.

Schedule Estimating Methodologies: The Promise of System Dynamics

> Most resource-constrained project scheduling research efforts have been made under the assumption that the project scheduling world is deterministic, while uncertainties during project execution are quite common. (Herroelen, 2005)

We continue this discussion of scheduling by comparing the traditional schedule estimation process with system dynamics. Clearly DoD project managers, engineers, estimators, and contracting officers have significant experience in developing project schedules. They also use the most modern scheduling software and processes. These tools are mainly based on the critical path method (CPM) and the program evaluation and review technique (PERT), which may be insufficient for the scheduling tasks at hand.

Accordingly, we use systems engineering methods to reduce the complex to its components rendered as the Work Breakdown Structure (WBS), and further reduce work to the work package level. These work packages are then defined and resourced and become the basis for not only scheduling, but cost and risk as well. WBS provides a decomposition of the project to a level that provides visibility of the work, as well as work progress. Once the effort is defined, schedule and the accompanying cost can be identified. The estimating effort is closely related to cost estimation and uses many of those same methods including analogy, parametric, algorithmic models, and expert judgment. Of these, expert judgment should be able to estimate the effort necessary to schedule the development tasks (Hughes, 1996). In fact, expert judgement is a first step for most cost and schedule estimating (Abdel-Hamid & Madnick, 1983).

Current Scheduling Methods

Scheduling tools (mainly based on the CPM and the PERT) apply a network approach to define critical activities, slack, and the overall time required to complete the development. The network approach also provides the basis for cost estimation, resource allocation, management focus and risk assessment, and provides a visual flow of the effort. However, given their work package or task level, CPM/ PERT force managers tend to develop a myopic view—for good reasons. The disadvantage is less focus on a systems view of the development effort. This leads to two major difficulties. First, CPM and PERT take a static view of project activities (Balaji & James, 2005), which fails to account for the relationships and interdependencies inherent in complex projects. Second, is the basic assumption that work proceeds as planned in the network—that there is a direct flow from work to be done, to work accomplished. That is, every CPM task has a discrete start and end—work is either started or not, finished or not. There is no accommodation for work that might not be done correctly or to the required quality (Cooper, 1993c).

Reality and empirical research show that work scheduled is not always completed to the necessary quality and therefore must be redone (Cooper, 1993b; Cooper, Lyneis, & Bryant, 2002; Rodrigues & Bowers, 1996).

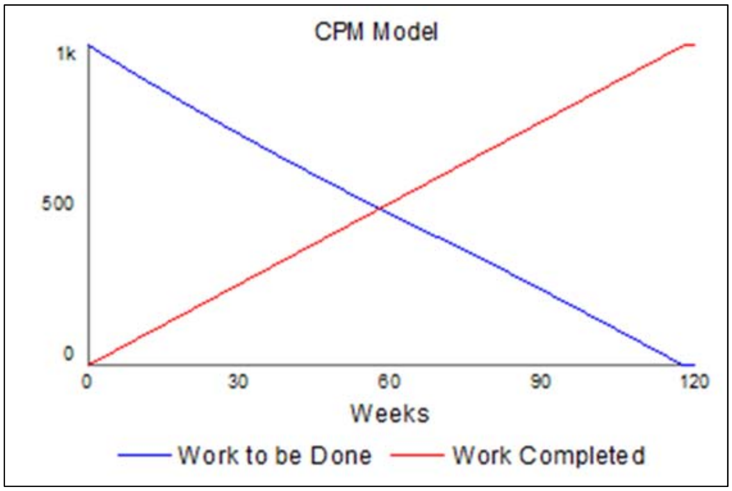

Figure 1. Generic Project Without Rework

Figure 1 shows a simplified, generic project with 1,000 tasks, executed by 10 people at approximately 90% productivity rate. The X-axis is weeks, and the Y-axis shows the number of tasks. The graph shows both a steady reduction in work to be done, and an equally steady increase in the work completed. The graph shows completion of these 1,000 tasks at week 117.5. The graph represents a deterministic view of scheduling that doesn't account for delays or changes in complex projects, whatever the cause. Proponents of CPM and PERT recognize the limitations resulting from the deterministic approach and have made attempts to incorporate more realism by adding probability measures to the estimated times, but the root problem remains (Kerzner, 2013; Moder, Phillips, & Davis, 1983).

The Dynamics of Projects

System Dynamics, a relatively new field, was developed by Forrester in the 1960s. It provides a conceptual modeling and simulation tool that uses differential equations to track the interdependencies, flow and dynamics of a process. Initially advanced as a management tool, it is also used to address broad policy issues, as well as project management (Forrester, 1987, 1995; Sterman, 2000; Williams, 2002). System dynamics “deals with the time-dependent behavior of managed systems with the aim of describing the system and understanding through quantitative and qualitative models” (Coyle, 1996, p. 5). It provides the project manager a different, system-level view of the schedule and its execution—to include cause and effect relationships; non-linearity; and understanding of the impact of feedback loops (Godlewski, Lee, & Cooper, 2012). System dynamics offers the possibility of augmenting traditional scheduling methods to provide not only better scheduling estimates, but better visibility of project status as well. The field gained recognition as a contract dispute resolution tool in the 1970s when it was successfully used to argue a weapons systems contract dispute with the U.S. Navy (Cooper, 1980).

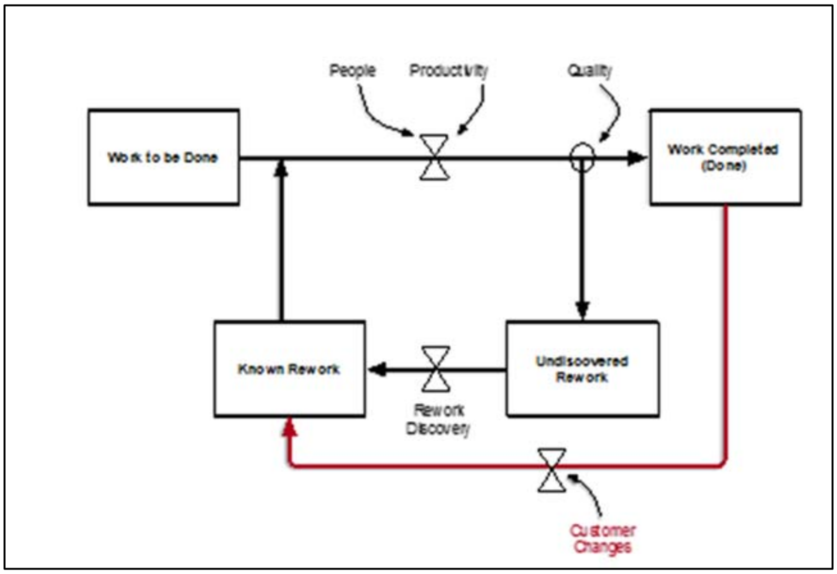

Figure 2. The Rework Cycle

The rework cycle is a fundamental system dynamic concept first articulated by Cooper (Cooper, 1993a, 1993b, 1993c). Figure 2 depicts the rework cycle. Unlike the CPM tracking of discrete tasks system dynamics monitors flows, the basic flow of work in a development is from *work to be done* (tasks or work packages) to *work completed*. Connecting that flow is a “valve” that regulates the flow. In the rework cycle, that flow is determined by *people* (numbers, skills, availability) and *productivity*. People times productivity provides a flow rate, for example, tasks per week. *Quality* is another modulator of the flow of work. Quality is simply a measure of whether the task was accomplished correctly and completely. Given the exploratory nature of research and development efforts, it is entirely possible that a planned development task fails to accomplish the task goal, and the task must be redone. Similarly, people may be operating at a high level of productivity, but not producing quality work.

There are two types rework, known and undiscovered. These categories are integral to the nature of weapons system development. Developmental test does identify some of the work that needs to be redone, and that work flows to the known rework stock. However, there is work that may pass developmental test, but is later found to be deficient (software “bugs” are a good example). Those deficiencies may not be discovered for significant amounts of time. Those deficiencies may also cause follow-on developmental efforts to slow or fail until they are finally discovered. Rework is a known issue for experienced project managers. Understanding the impact of the rework cycle coupled with the CPM network can provide a tool to develop better schedule estimates.

The red arrow (lower right) in Figure 2 is an example of the dynamic, causal effects system dynamics can track. In this case, customer changes add to the basic rework cycle by measuring the impact customer changes can have on a development. In the DoD, “customer” includes the program office, the acquisition chain of command, and the requirements community. Customer changes are shown as a valve that affects the flow of work that may be complete, by delaying the flow of the work both from changes as well as delays from information gathering, preparing, and reporting. For instance, the GAO found that the F-22 Increment 3.2B Modernization spent 3800 staff days to prepare 33 milestone documents and present 74 briefings for the Milestone B process (GAO, 2015). This work had a cost of some $10 million. These 3800 staff days obviously would also have impacts on the schedule, potentially more significant than on cost. Another schedule impact is driven by the customer changing requirements, specs, or simply delaying responding to information guidance requests from the PMO.

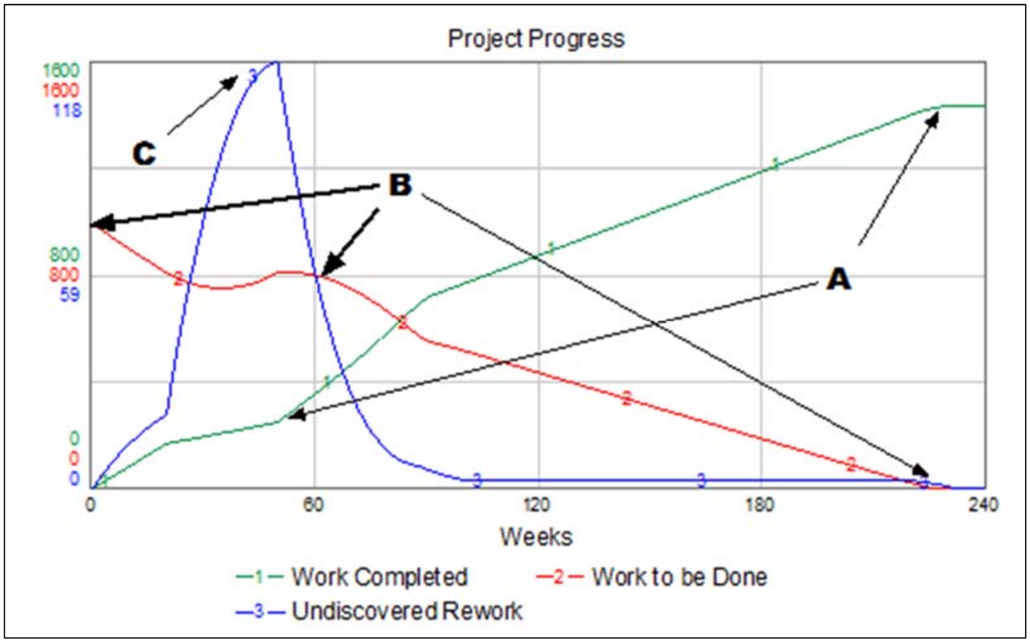

Figure 3. Effect of Rework on Generic Project

Figure 3 shows the results from the same generic model used in Figure 1, but this time incorporating the impact of the rework cycle. The X-axis shows time, and the Y-axis indicates number of tasks. Line A, shows the Work Completed, line B shows Work to be Done, and line C shows a generic calculation of Rework. Comparing line A in this graph to that of work completed plot in Figure 1 demonstrates the effects of rework. In this case rework peaks at week 48 (line C), and is estimated at 75%. This means three of every four tasks must be redone, a conservative estimate by some measures especially when considering software development projects (Cooper & Mullen, 1993). Similarly, line B (Work to be Done) shows a much longer completion time than that of Figure 1. Completion time in this model run is 229 weeks, an increase of 111.5 weeks over the generic model in Figure 1, an almost 100% increase in schedule. Another way of considering the impact of rework is that instead of the 1,000 tasks originally required, the number of tasks completed was 1,437—a significant increase in work requiring more time and money.

While this is an elementary model, it demonstrates that something as simple as rework (because of quality) can have a significant effect on project schedules. It also validates an oft repeated axiom in defense acquisition—a design freeze, made possible by effective systems engineering "portends better program outcomes" (GAO, 2016b).

Summary

Weapons system development is itself a system—a collection of inputs and outputs, events and activities that interact over time to produce a unified whole. Dynamics describes the forces or properties that drive change within a system over time. Thus, system dynamics describes the change within a system over time—a stochastic perspective. And managing change is key to effective program management.

The deterministic schedule estimating methodology in use in the DoD today is defined by CPM. This perspective assumes each task is discrete, and does not account for interaction and interdependency. It also assumes each task is either completed correctly and completely the first time, or that any necessary further work is included in downstream estimates (Reichelt & Lyneis, 1999). DoD project managers know this is not the case. Thus, system dynamics combined with current CPM-based approaches provide the potential to meet the need to better estimate weapon system development schedules.

The F-35 Case: A First Look at Tradeoffs Among Performance, Cost, and Schedule

A useful step toward better schedule estimation is to better understand the nature of the major tradeoffs in acquisition program management: cost, performance, and schedule. Application of paradigms such as Systems Dynamics (above) is one such approach. Another is case studies of actual acquisition programs.

Accordingly, this section provides a preliminary case study of tradeoffs in the Joint Strike Fighter (F-35) program. We pose three questions:

1. What sorts of trades were made in the F-35 program after the 2001 source selection decision?
2. What were the consequences of those trades?
3. How and why were those trades made?

JSF Intentions at the Start

During the early 1990s, a number of tactical fighter programs and initiatives were cancelled—with the common theme being affordability. These included the Navy's A-12 attack fighter, the Naval Advanced Tactical Fighter (F-22 variant), and the Air Force Multi-Role Fighter (DoD, n.d.-c). The focus shifted to jointly designed and procured systems. This included a number of STOVL-capable initiatives, to include the CALF (Common Affordable Lightweight Fighter, 1993–94)—intended to develop "technologies and concepts" to support Harrier replacements for the USMC and Royal Navy, plus a highly-common conventional aircraft for the USAF (DoD, n.d.-c).

The surviving initiatives were combined under the JAST (Joint Advanced Strike Technology) program, which began operations in January of 1994. JAST's original charter was to "mature technologies, develop requirements, and demonstrate concepts for *affordable* next-generation joint strike warfare" (emphasis added; DoD, n.d.-b).

This theme was strongly echoed in a Defense Science Board (DSB) study published later that same year (DSB, 1994). The DSB's findings and recommendations strongly emphasized (a) well-specified operational capabilities (esp. p. ES-2), (b) "affordable processes and end products" (ES-2), (c) technical conservatism ("a customer for technology, not a … developer" [ES-2]), and a strong emphasis on affordability (calling for "revolutionary improvements in affordability" [ES-4], described as the "key enabling technology" [ES-5]).

Similar themes appeared in a 1997 paper by RADM Steidle. He emphasized "doing business differently" through "streamlined, nontraditional business approaches" (p. 7). These included Government-Industry teamwork, Cost as Independent Variable (CAIV, in the interests of affordability), and using best practices ("sound ideas for improvement"; Steidle, 1997, p. 7).

These practices included pursuing affordability through a high degree of commonality among all services' variants (Steidle, 1997, p. 9), choosing autonomic support as "the … logistics response to … enhanced onboard weapon system diagnostics" (p. 9), and pursuing extensive cost-performance tradeoff studies (pp. 9–11).

Accordingly, the first JSF Selected Acquisition Report (SAR) stated that "the cornerstone of the JSF Program is affordability" (Steidle, 1996, p. 2).[1] And, fully consistent with DSB recommendations, committed the program to "fully validated, *affordable* operational requirements," (emphasis added), technical risk reduction, and "demonstrating operational concepts" (p. 3).

What Resulted

> "There's not a more complex program on the planet. … We did it because we had this grand vision."—(then) Maj Gen Christopher Bogdan (2012)
>
> "Our complexity reach exceeds our engineering grasp."—Anonymous DoD official (2011)

It seems clear the JSF we originally wanted is not the JSF we're getting. The CALF (Common Affordable Lightweight Fighter) initiative was intended to design demonstrator aircraft to include affordability analyses—with few hard constraints. And the JAST (as noted above) heavily emphasized affordability and technological conservatism. The JSF is not even close to these original visions, as illustrated in Table 1.

The F-35 is a much more capable aircraft than the Joint Strike Fighter originally envisioned. According to Lockheed-Martin, the F-35 has (or will have) a wide range of capabilities, of which air-to-ground attack is merely one (LM, 2017). More importantly, the F-35 that is emerging embodies new concepts of warfare based on situational awareness shared through secure networks. The overall effect according to one source is that the F-35 "*will be part of a strategic transformation*. The ability of the aircraft working with the other elements … will allow tactical maneuver to have a strategic consequence" (Laird, 2012).

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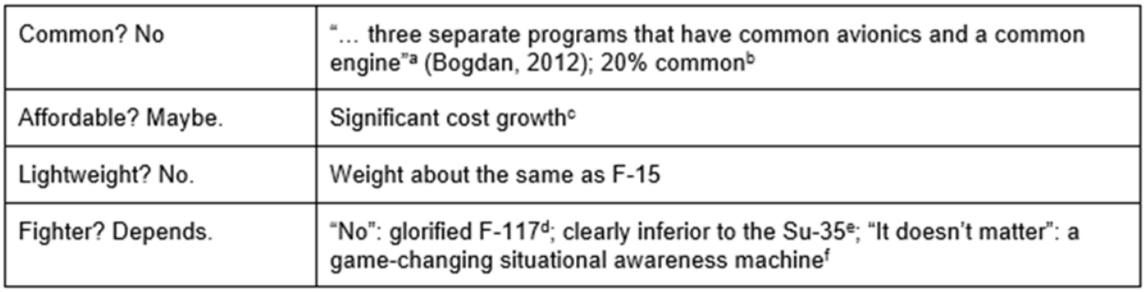
[1] This exact statement appeared in JSF SARs for more than a decade, and is still posted on the DoD's JSF History website (last accessed in 2017).

Table 1. Joint Strike Fighter vs. CALF



Common? No	"… three separate programs that have common avionics and a common engine"[a] (Bogdan, 2012); 20% common[b]
Affordable? Maybe.	Significant cost growth[c]
Lightweight? No.	Weight about the same as F-15
Fighter? Depends.	"No": glorified F-117[d]; clearly inferior to the Su-35[e]; "It doesn't matter": a game-changing situational awareness machine[f]

Notes: a. Bogdan (2012); b. Seligman (2017); c. GAO (2016a, p. 10); d. Anonymous AF Fighter Weapons School Instructor (2015); e. Airpower Australia (2017); f. Laird (2012)

Consequences: The Price of Performance

However, increased performance has come at a high price—in both schedule and cost. The multiple program redefinitions ("re-baselining") complicate measurement somewhat, but nonetheless cost has grown significantly, and schedule has stretched (GAO, 2016, p. 10). The indirect effects of F-35 funding additions and delayed operational capability have likewise been significant (Sweetman, 2012; Freedburg, 2017; Tirpak, 2017b).

The F-35 program has encountered a large and complex list of complex problems. Those difficulties, and the management actions to deal with them, similarly constitute a highly complex history. Highlights include the Quick Look Review of 2011 and continuing operational testing issues.

The Quick Look Review was an OSD-mandated study of F-35 development issues. The team found no show-stopping "fundamental design risks," but did identify a total of 13 issues, of varying significance. Program concurrency was identified as a matter of overarching concern (Axe, 2011).

Since then, both the Marine Corps and Air Force have declared Initial Operational Capability for their models, and a number of program issues have also been resolved. However, significant problems still remain. The F-35 section of the *FY2016 Annual Report* from the DoD's Director of Operational Test and Evaluation (DOT&E; 2016) identified a number of concerns including the following:

- Testing schedule delays (p. 47),
- Air frame issues including vertical tail attachment bushing fatigue (p. 48),
- Mission Data File production capacity (p. 49),
- Autonomic Logistics Information System (ALIS) capabilities for full combat capability expected after declared IOCs (p. 68), and
- Weapons release limitations (p. 62).

None of these are trivial. For example, "if we don't get ALIS right, we don't fly" (Bogdan, 2012). It's a safe bet that these problems, plus the others DOTE identified, are solvable. It's a safer bet that they will further delay, and make more costly, fielding of F-35 combat capabilities.

How and Why Were the Trades Made?

As a first step in answering this question, we drafted a list of keywords associated with information and network-based concepts of operation cited by current F-35 advocates. We then consulted readily available sources for consideration.

Unclassified documents such as the Joint Strike Fighter Selected Acquisition Reports (starting in 1996) unearthed surprisingly little congruence with current F-35 concepts of operation. For example, “situational awareness” discussions emphasized the JSF as a consumer of offboard information, with much less attention to the aircraft as a source (or sharer) of information. Similarly, the term “network” appears with a fair degree of regularity, but mostly referred to means of testing and evaluation—with some addressing the JSF’s role in a future system-of-systems architecture. There was, for example, no mention of the battle-management role now widely discussed (e.g., Weisgerber, 2016).

Our inquiry did, however, yield some interesting bits. These included RADM Steidle’s (1997) rationale for autonomic logistics as a logical extension of onboard fault-detection systems. In retrospect, this could have been the first along the primrose path to current ALIS difficulties. We also have Gen Bogdan’s (2012) intriguing reference to a “grand scheme” for the JSF. We hope to learn more in future inquiries.

Answering the Questions

Were cost-performance-schedule trades made? Our answer is “yes.” Relative to the JAST conception, there were major trades made for improved performance. This conclusion seems unsurprising, and is likely a matter of common knowledge among members of the acquisition community.

Their consequences? Choosing higher performance was a major factor in explaining cost overruns and schedule delays. Parts of Gen Bogdan’s “grand vision” (2012)—such as the helmet mounted display unit and autonomic logistics information systems—have resulted in long-term difficulties, causing delays and costing money. In addition, attempts to keep the program closer to planned schedule appear to have increased program concurrency, which in turn has been a cause of cost growth and schedule delays.

How and why were the tradeoffs made? From the references consulted, we were unable to find more than fragments from the record of how and why the JSF went from a conservative, relatively specialized concept aircraft to an “extraordinary” multi-role combatant (Miller, 2016).

This has been an initial inquiry, and the answers appear beyond the limits of the open literature. More complete answers entail more work, to probably include field interviews.

Better Understanding Acquisition Schedules Through Better Performance Measures

There are a number of good reasons to estimate combat performance for modern systems (and systems of systems) that encompass both acquisition management and defense planning (Table 2 below). For example, the new fifth generation of combat aircraft conducts air warfare in significantly different ways. As one Air Force officer put it, “With fourth-generation fighter airframes, speed and energy equaled life and survivability. In the fifth-generation realm, information equals life” (Fraioli, 2016).

Hence, planning for information-age combat forces would benefit from better understanding of combat effectiveness. As a Marine fighter pilot put it, “We need to do a better job teaching the public how to assess a jet's capability in warfare” (Lockie, 2017).

Table 2. Air-Air Combat Tasks (Kill Chain)

TASKS	CAPABILITIES
Cueing	Intelligence, Surveillance, & Reconnaissance (ISR)
Detection, Identification, & Tracking	Sensors
Allocation of Forces	Command & Control (C2)
Engagement	Platforms & Weapons
Assessment	ISR

Second, The JCIDS (Joint Capability Integration and Development System) Instruction recommends “effective cost, performance, schedule and quantity trade-offs” as being highly conducive to successful acquisition programs (CJCS, 2015, p. A-9). Making those tradeoffs well informed presupposes there’s some useful way to measure performance.

Finally, better understanding of performance has real potential for explaining (and predicting) system development schedules—analogous to use of performance indexes (scalars) in explaining cost of previous generations of fighter and attack aircraft (Hildebrandt & Sze, 1986). That is, better measures of performance may lead to better schedule estimating methods.

Hence, our purpose in this section is to start a discussion about measuring performance in Information Age warfare. We hope readers find some useful insights in what follows.

The basic Lanchester model is primarily about the engagement task. But military affairs have gotten more complicated. The variants discussed below are a first step in widening that analysis. This section considers “detection, identification & tracking” (shortened to “detection”), Allocation (C2), in addition to expected results of engagements.

Lanchester Aimed-Fire Model

Results in the basic Lanchester aimed-fire model[2] (best known of the genre) depend on numbers (B and R) and “lethality” (b and r). At any given moment in a Lanchester battle,

$$dR/dt = -\,b * B \text{ and } dB/dt = \,-r * R \qquad (1)$$

Blue (Red) lethality, b(r) depend on Blue’s (Red’s) rate of fire, accuracy, and lethality of munitions. Blue (Red) lethality also depends on Red (Blue) ability to counter, evade, or nullify the effects of that fire.

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[2] Studies in the Lanchester tradition have resulted in numerous, varied, and highly ingenious analyses. Taylor (1983) and Bracken, Kress, and Rosenthal (1995) are but a few examples.

While casualty rates (r*R and b*B) are important, casualties as fractions of the respective forces determine the winner. Thus,

$$(dR/R)/(dB/B) = \left(b * \left(\frac{B}{R}\right)\right)/\left(r * \left(\frac{R}{B)}\right) (b*B^2)/(r*R^2),$$

And numbers count more than unit lethality in determining military effectiveness. That is,

$$E(R) = r*R^2, \text{ and } E(B) = b*B^2. \qquad (2)$$

A Lanchester Model with Probability of Detection Varying

The basic Lanchester model embodies assumptions that do not reflect information-age air combat well. Among other things, we should explicitly consider the possibility of not all combatants present being detected well enough to support a targeting solution.

This affects casualties inflicted. If, for example, half the Blue force disappears (in effect) from Red's situational picture, then available Red units must concentrate their efforts against fewer targets—with Red's fire having less effect on the entire Blue force. Basically, we assume Red forces concentrate their fires on the detected Blue forces, and must leave the rest alone.

In general, therefore, we can describe rate of casualties for Red on Blue as follows:

$$\text{If } P_{dR}*R>B, \text{ then } dR(t) = -b*B(t)*, \qquad (3)$$

$$\text{and if } P_{dR}*R<B, \text{ then } dR = -[(1-PM_R)\text{^}(B/(R*P_{dR})], \qquad (4)$$

is a reasonable approximation.

Hence, varied detection probabilities (degrees of stealth) can change the relationship of relative force sizes in the outcome. Also noteworthy is that stealth needn't be absolute to be operationally significant.

One summary of our simple exercise is the following estimating equation:

$$dR/R = - 0.22 + 0.30*(B/R) + 0.12*PdR +0.19*b + 0.04*C2 – 0.13*(PdR\text{^}2) – 0.02*(b\text{^}2) – 0.10*(C2\text{^}2) + 0.49*(PdR*b) + 0.08*(PdR*C2) +0.13*(b*C2) \qquad (5)$$

where the variables' are defined as follows:

(dR/R) is the estimated proportion of Red force attrited by Blue fire,

(B/R) is relative force size (Blue vs. Red) at the start of the engagement,

PdR is probability of detecting Red units (0 to 1),

b is Blue units' lethality vs. Red units (0 to 1),

C2 is degree of command and control (0 to 1).

The linear variables provide the "direct" effects. The squared terms indicate how the direct effects are modified as their size increases. If the coefficient is negative (as all are), then incremental effect decreases as the variable increases—also known as "diminishing returns."

The multiplicative terms indicate the interactions among the variables. If the coefficients are positive, then there is a "synergistic" effect among the variables. Also, it means that ability to substitute one attribute for another decreases as it increases—"diminishing marginal rate of substitution."

Figure 4 illustrates this point. If the probability of detecting Red (PdR) decreases from 0.8 to 0.6, an increase of 0.05 in Blue lethality (b) can compensate. However, it takes an increase of 0.25 in b to compensate for a reduction PdR from 0.4 to 0.2.

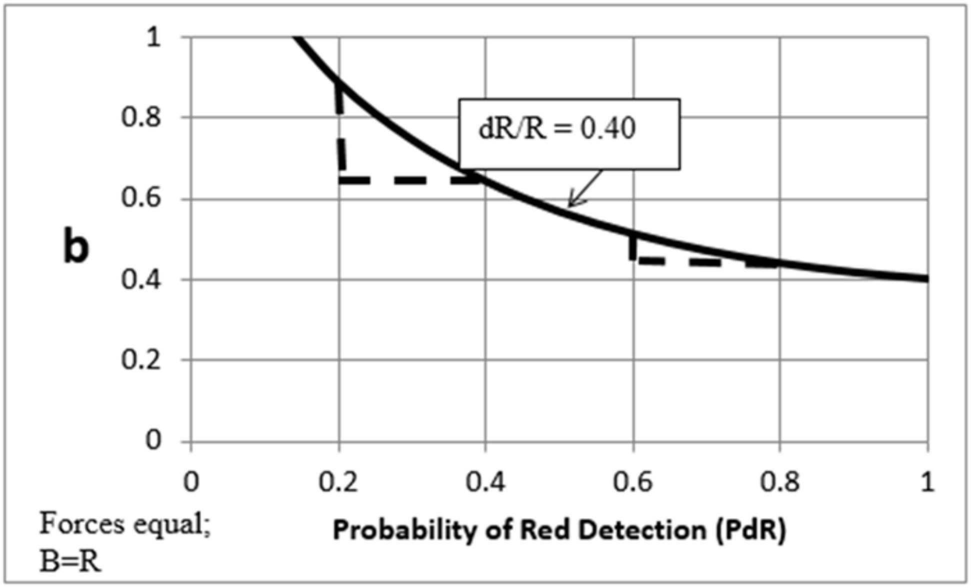

Figure 4. Red's Proportion Lost vs. Blue Lethality (b) and Probability of Red Detection (PdR)

Measuring Air-to-Air Firepower

What's above is a first step in measuring air-to-air firepower. Figure 5 provides an approach to a more complete measure of capability. Air combat power is basically ability to accomplish the stated tasks given. The goals hierarchy essayed in Figure 5 centers on the "engagement" task with "fire power" as metric of capability.

One should not expect all the sub-goals (like sensor vs. weapons capabilities) to be equally important. Likewise, we can expect interactions among the sub-goals in enhancing firepower (as shown in Equation 5 above).

The task ahead is to combine good analysis and expert judgement to formulate an estimate for "firepower" as a function of Command Control, Force Size, Sensors, Shared Situational Awareness and Weapons. While this is large and complicated effort, it also appears to be tractable.

Closing Comment: Fighting Outnumbered and Winning

"The pilots will … penetrate contested space and are likely to be outnumbered by adversary aircraft" (Miller, 2016).

However, the advantages of more stealth[3] are more completely observed in force-on-force models. The Air Force Chief of Staff speaking at a recent event dismissed one-on-one comparisons fighter types (such as F-22 vs. J-20) as not really relevant, and indicated that net assessments of network vs. network are crucial (Tirpak, 2017a).

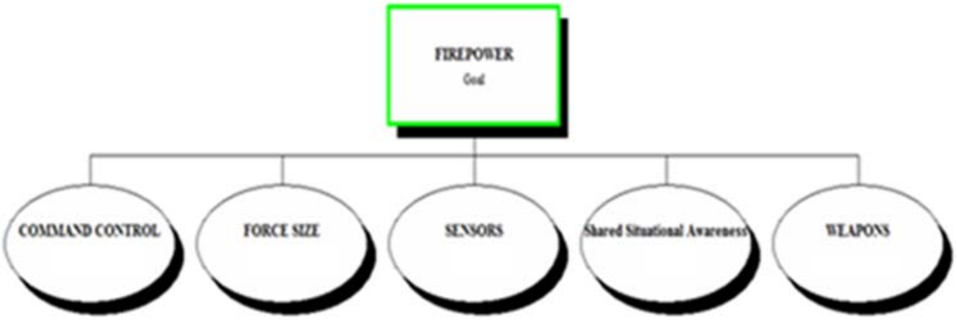

Figure 5. A Draft Goals Hierarchy for Estimating Air-to-Air Combat Potential

To illustrate, Figure 6 displays Blue stealth (PdB) needed to win vs. the probability of detecting Red units (PdR). Within the scope of a simple force-on-force model, Blue wins in all combinations of detection probabilities in the lower right; Red wins to the upper left. Toward the right side of the figure, weapons matter more; at the left, stealth matters more.

The horizontal scale (0–1) compared to the vertical (0–0.4) is worth noting. It takes a significant Blue stealth edge to overcome the advantage of superior numbers. Or as Air Combat Command's General "Hawk" Carlisle put it, "Fighter technology really isn't the problem. It's really about numbers"[4] (Tirpak. 2017c).

That said, however, increasing Blue lethality (b) also provides considerable advantage in countering superior numbers. These results are preliminary and suggestive. At best they provide some useful insights. Next steps are to finish development of this model further and then verify and validate it.

Such a model, combined with appropriate expert judgements, can lead to useful performance measures. The performance measures, in turn, can provide inputs for credible schedule estimates.

We have departed from measuring platform-on-platform capabilities and into the realm of force-on-force. In an era of systems of systems and network vs. network that seems appropriate.

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[3] We mean "stealth" in a broad sense: the ability to avoid being engaged. Detection, identification and tracking sufficient to support an engagement can be denied by a number of means—to include various forms of information and electronic warfare, as well as through low-observable platforms.

[4] This statement may appear more strongly than Gen Carlisle intended it. Nonetheless it points out the continued relevance of comparative force sizes.

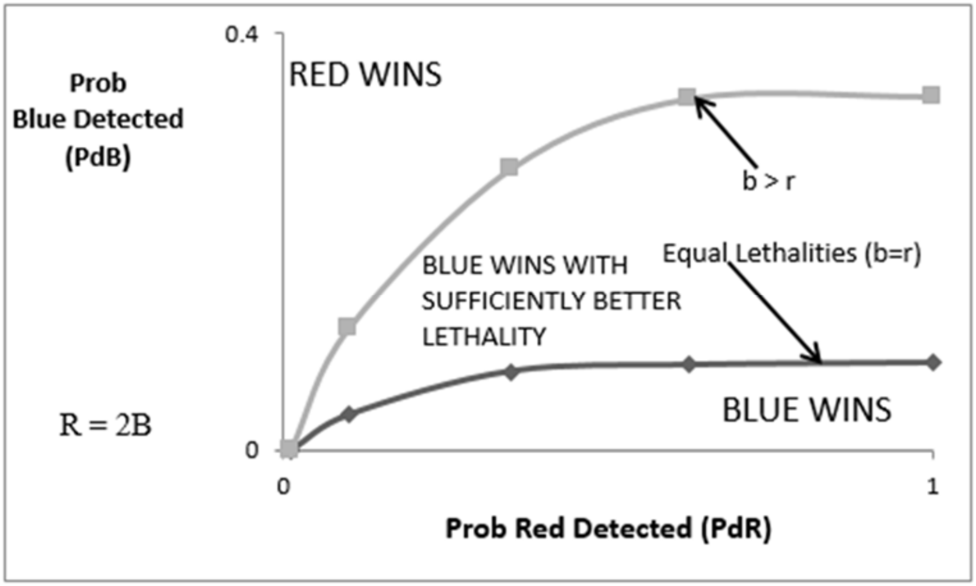


Figure 6. Stealth and Lethality in Overcoming Numerical Disadvantage

Program and Contract Schedule Uncertainty: Data Sources and Empirical Models

This section focuses on schedule changes and their associated cost and uncertainty during the Acquisition Process. Clearly, in light of the relationship between total cost growth and schedule and performance growth, it is necessary to explore in greater depth the information underlying total program acquisition cost. At the program level, this information is available in SARs; at a lower level, information is available in the Earned Value Management (EVM) system.

First SAR data are considered. The change in the acquisition cost associated with schedule constitutes one cost change among a specified group of program-level categories that experience cost changes. These changes underlie the total acquisition cost growth of Major Defense Acquisition Programs (MDAPs). The purpose of this analysis is to increase understanding of linkages among schedule categories within the acquisition process, and pave the way for a more complete understanding of the causes of schedule uncertainty.

It is helpful to begin with a brief discussion of total program cost growth, and then turn to the categories that identify cost changes—called "Program Variance" for a particular category. These categories are Program Schedule Variance, and Program Engineering Variance. Delving deeper, programs are typically underwritten using contracts. These contracts constitute the next lowest level for explaining the effects of schedule uncertainty. In fact, in each SAR report there are one or more contracts for which Earned Value Management data are reported on an annual basis. Annual data for these variances are contained in the Selected Acquisition Reports (SARs)

Several points should first be made about total program acquisition costs, which constitutes the top line for acquisition cost analysis and reporting. A significant portion of DoD Acquisition research has been devoted to the prospective breach of specified cost thresholds. Of particular importance are the thresholds mandated by Congress, which must be informed of significant breaches through Nunn-McCurdy Unit Cost Reporting.

These breaches would be monitored by the DAB, which establishes the Acquisition Defense Baseline (ADB). The ADB can change if a significant restructuring of the program occurs and there are new baseline cost estimates. A breach of the thresholds for both the Current Baseline Cost Estimate and the Original Baseline Cost Estimate would be of concern to both Congress and the acquisition community.

The Original Acquisition Program Baseline is determined at the time of Engineering and Manufacturing Development (EMD) approval (or Milestone B). These average costs are measured in relevant base year dollars (BY$): APUC equals ((Total Development + Procurement+ Construction) (in BY$)/Total Program Quantity), while PAUC equals (Total Procurement in BY$)/(Procurement Quantity).

It is important to understand that these cost growths are not directly associated with cost overruns that occur on contracts when the estimated final price rises above the current target price. Rather they result from a re-estimation of the effects of changes in the program parameters that are associated with the categories identified in the SAR reports, and, in turn, with the growth of total program acquisition costs.

Cost growth includes instances relating directly to schedule and indirectly to schedule via changes in the performance specifications. While specification changes can occur without changing the ABP, if there is a major restructuring of the program, the ABP may be changed by the DAB. This type of change could occur several times during the course of the acquisition process.

Under the purview of the Defense Acquisition Board (DAB), Performance and Schedule Breaches are also evaluated. These result from failures to meet specified Threshold Performance and Schedule values, where the Threshold values are typically lower than the Objective values.

Objective Schedule and Performance can be viewed as those levels that are “Best Value” to the government. These are the values that minimize full cost, which includes both accounting and implicit costs. Implicit costs might include costs of schedule slips.

Threshold Schedule and Performance, in contrast, refers the specified levels that are minimally acceptable to the government. With respect to Schedule, the delivery of different systems needs to be synchronized, and there is a cost associated with late delivery that affects this requirement. Also, if delivery is significantly late, a prior generation system may need to be retained in the inventory longer than anticipated at the same time as the effects of aging are incurred. There might also be an implicit cost from not achieving an Objective Performance level. In this case, minimum acceptable (Threshold) schedule and performance levels may be specified, with failure to achieve constituting a breach.

However, an examination of Selected Acquisition Reports indicates that frequently only Objective schedule and performance levels are specified. In this situation, a failure to meet Objective schedule milestones or the Objective levels of the relevant performance parameters would constitute a breach. In certain situations, however, a six-month delay in meeting a schedule milestone would constitute a breach.

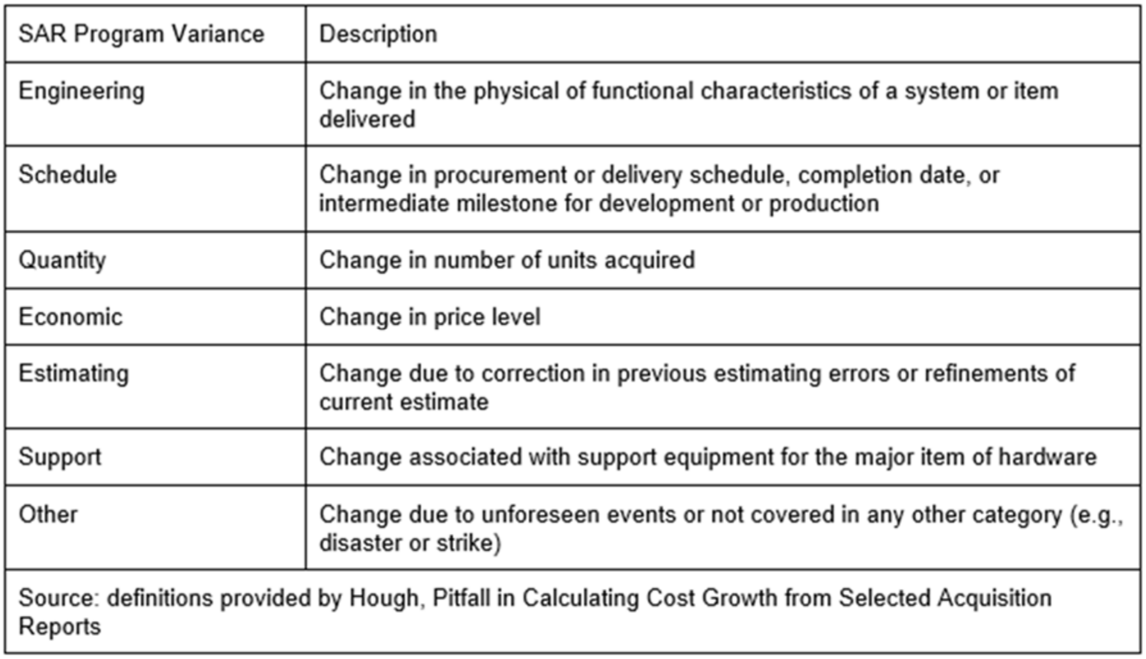
Selected Acquisition Reports as Data Source

Program Variance information is reported in each annual SAR for selected categories. For each category, these variances are estimates of differences between the revised estimated final acquisition cost and the previous program development cost estimate. The development cost estimate is the total acquisition cost estimate developed at the time EMD is initiated.

Table 3 contains information specifying the different program variance categories identified in each SAR. Given these definitions, one can infer that the information reported for Program Engineering Variance and Program Schedule Variance reflects cost changes associated with contractually supported changes to the program. Both of these program variances can have a significant effect on the schedules that end up being achieved in the program. One might also expect Program Quantity Variance to have a significant effect on cost. However, there remains uncertainty as to how this program variance category should be analyzed, so in this preliminary analysis Program Quantity Variance will not be addressed. With respect to Program Economic Variance, the cost data are typically converted to constant dollar values by removing the effect of the price changes that Program Economic Variance embodies.

Calculations of cost breaches that fall under the Nunn-McCurdy requirements, would take account of the changes in cost associated with all of these SAR program variances, net of Program Economic Variance. The only difference would be that, for Nunn-McCurdy calculations the baseline cost would be that associated with the APB. For the SAR variances, the baseline would equal the program cost estimated at the time EMD is approved.

Table 3. SAR Program Variance Categories



SAR Program Variance	Description
Engineering	Change in the physical of functional characteristics of a system or item delivered
Schedule	Change in procurement or delivery schedule, completion date, or intermediate milestone for development or production
Quantity	Change in number of units acquired
Economic	Change in price level
Estimating	Change due to correction in previous estimating errors or refinements of current estimate
Support	Change associated with support equipment for the major item of hardware
Other	Change due to unforeseen events or not covered in any other category (e.g., disaster or strike)

Source: definitions provided by Hough, Pitfall in Calculating Cost Growth from Selected Acquisition Reports

Earned Value Management

To dig deeper, we turn to contractual data that underlies program data. Cost Variance (CV) is defined as follows:

$$\text{CV} = \text{BCWP} - \text{ACWP}, \tag{6}$$

where BCWP = Budget Cost of Work Performed and ACWP = Actual Cost of Work Performed. In turn, Schedule is defined as

$$\text{SV} = \text{BCWP} - \text{BCWS}, \tag{7}$$

where BCWS = Budgeted Cost of Work Scheduled.

These contract variances are depicted in Figure 7. In this case, the upper curve displays ACWP. Any time ACWP this is higher than BCWP, there is a cost overrun. The CV is therefore negative, which (counterintuitively) is typically an unattractive outcome. One measure of cost productivity would be ACWP/BCWP.

SV is somewhat more difficult to interpret. If BCWP is less than BCWS, then the scheduled work budgeted is greater than the work actually completed. That is, the work scheduled to be produced is less than the work actually produced, and the contract is behind schedule. A measure of schedule achievement productivity at this time is BCWP/BCWS.

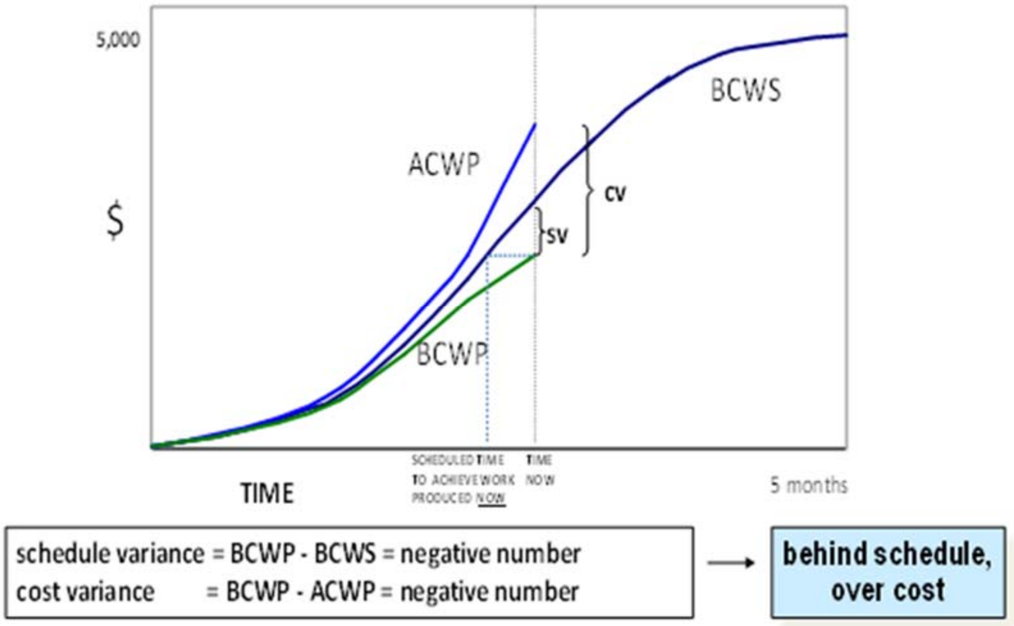


Figure 7. Depicting Contract Variances

A question that impacts empirical work concerns the relationship between Program Variances and Contract Variances. As indicated, we restrict our focus to Program Engineering and Program Schedule Variance. The issue is how these relate to Contract Cost and Schedule Variance.

Worth noting is that each Program Variance is forward looking, and identifies estimated changes over the remainder of the program resulting (say) from specification changes. While Contract Variance is conceptually determined at a point in time, available data typically applies to some period of time such as a month, quarter, or year. It is for these time periods that cost and budget data are typically collected.

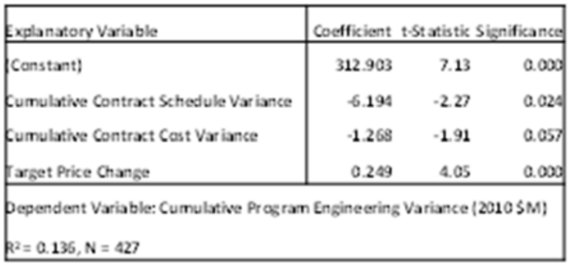
Empirical Analysis

Using the contract cost and budgetary data for a particular period does not seem to be an appropriate way to explain program variances that are associated with cost changes over the remainder of the program.

Also reported in the SARs and EVM documents are cumulative Program and Contract Variances. The cumulative program variances represent sums of projected cost changes since the date of the latest APB; the sums of contract variances represent aggregations of historical cost and budget information associated with work produced and work scheduled. These historical aggregations of **program and contract variance** overrun and underrun data are likely to be more effective in explaining the SAR program variance projections. Basically, if historical aggregations or budget and cost information indicate a tendency for outcomes to occur that are above budget and behind schedule, then, aggregations of SAR variance projections over time should be significantly related to the aggregation over time of contract variances. *Therefore, in the following empirical analysis, we use cumulative values of the program and contract variances.*

Two empirical results are displayed that result from the analysis of 31 SAR programs. In Table 4, Cumulative Program Engineering Variance is related to the two cumulative contract variances.

Table 4. Cumulative Engineering Variance Model



Explanatory Variable	Coefficient	t-Statistic	Significance
(Constant)	312.903	7.13	0.000
Cumulative Contract Schedule Variance	-6.194	-2.27	0.024
Cumulative Contract Cost Variance	-1.268	-1.91	0.057
Target Price Change	0.249	4.05	0.000
Dependent Variable: Cumulative Program Engineering Variance (2010 $M)			
R^2 = 0.136, N = 427			

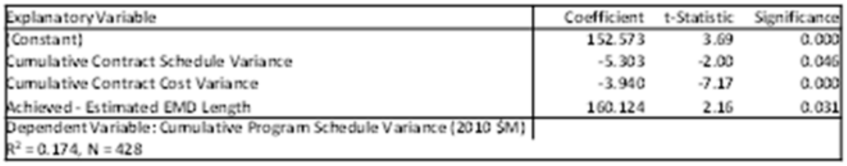
After controlling for Target Price Change experienced by each contract, we find that both Cumulative Contract Schedule Variance are significantly negatively related to Cumulative Program Engineering Variance. The negative sign is plausible because increases in the contract variances reduce budget overruns and schedule slippage. Both of these reductions are shown to be associated with reductions in Cumulative Program Engineering Variance, that is, a decline in the cost growth of this program cost category.

The more negative coefficient of Cumulative Contract Schedule Variance suggests that contract schedule slippages are more likely to impact program performance specifications than contract outcomes in which actual cost is greater than budgetary cost.

In Table 5, after controlling for the relationship between EMD Achieved and Estimated EMD length, we find that both contract variances are negatively related to Program Schedule Variance. This is similar to the result shown in Table 4, and is consistent with expectations.

Once again, Contract Schedule Variance has a larger impact on Program Schedule Variance than Contract Cost Variance. Contract schedule slippages have a somewhat larger impact then being over contract cost expectations.

Table 5. Cumulative Program Engineering Variance Model



Explanatory Variable	Coefficient	t-Statistic	Significance
(Constant)	152.573	3.69	0.000
Cumulative Contract Schedule Variance	-5.303	-2.00	0.046
Cumulative Contract Cost Variance	-3.940	-7.17	0.000
Achieved - Estimated EMD Length	160.124	2.16	0.031
Dependent Variable: Cumulative Program Schedule Variance (2010 $M) $R^2 = 0.174$, N = 428			

Comments

One can probably reach an understanding of the linkages between program cost growth, SAR program-level cost variances, and contract-level data developed during the Earned Value Management process. However, the empirical relationships found between contract variances and both program engineering variance and program schedule variance require additional analysis. Typically cost variances are computed when there is no change in contract specifications. However, the SAR Engineering and Schedule Variances are dependent on those changes. Contract variances when they are negative may induce changes in performance specifications. However, this requires further analysis.

A useful next step is to focus in on the F-35 using a more detailed EVM data set. Explicitly included in the analysis would be schedule milestones and changes in the APB that have occurred. Hopefully, this will help answer some of the remaining open questions.

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