SYM-AM-16-029

PROCEEDINGS
OF THE
THIRTEENTH ANNUAL ACQUISITION RESEARCH SYMPOSIUM

WEDNESDAY SESSIONS
VOLUME I

Toward Realistic Acquisition Schedule Estimates

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Published April 30, 2016

Prepared for the Naval Postgraduate School, Monterey, CA 93943.

The research presented in this report was supported by the Acquisition Research Program of the Graduate School of Business & Public Policy at the Naval Postgraduate School.

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Panel 4. Strengthening Schedule Estimates in MDAPs

Wednesday, May 4, 2016	
11:15 a.m. – 12:45 p.m.	**Chair: Rear Admiral Thomas J. Kearney, USN,** Director, Acquisition, Commonality, & Expeditionary Warfare, Naval Sea Systems Command ***Acquisition Cycle Time: Defining the Problem*** David Tate, Institute for Defense Analyses ***Schedule Analytics*** Jennifer Manring, Principal Economics and Business Analyst, The MITRE Corp. Thomas Fugate, Principal Acquisition and Program Management Analyst, The MITRE Corp. ***Toward Realistic Acquisition Schedule Estimates*** Raymond Franck, Professor Emeritus, U.S. Air Force Academy Gregory Hildebrandt, PhD Bernard Udis, Professor Emeritus of Economics, University of Colorado at Boulder

Toward Realistic Acquisition Schedule Estimates

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Abstract

Time needed to develop and field new military capabilities is becoming an increasingly serious problem. Among other things, development times have steadily increased. In this paper, we attempt to structure the schedule estimating problem, present some initial results, and propose a research agenda to improve schedule estimating. Accordingly, we seek preliminary answers to the following questions.

- What is the current state of the art for estimating acquisition program schedules? What should it be?
- What are salient features of program management trade-offs, especially between schedule and cost (which are related in complex, imperfectly understood ways)? In what areas should air combat performance measures need updating?
- What are the elements of a research agenda for learning more about schedule estimating?

We also present some preliminary results in the form a narrative case study of the F-35 program and empirical estimates of schedules.

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). However, these attributes have received rather unequal interest—with cost garnering the most attention.

For example, in the DoD’s latest acquisition performance report (DoD, 2015), “cost” appears 18 times in the table of contents and 86 times in the highlights; “schedule” appears six times in table of contents and 37 times in the highlights. (“Operational performance” appears only six times in the contents.) In our conference program, “cost” appears 14 times in five sessions, while “schedule” appears four times, in one session.

Cost is certainly important, and warrants much attention, which it's received. The DoD has devoted considerable time, attention and resources to more realistic cost estimating. And, seems to us, there's been a great deal of progress toward that goal.

But schedule is also important and is becoming more so. With multiple Revolutions in Military Affairs ongoing simultaneously, we have entered a hyper-adaptive era in military affairs—enabled, inter alia, by rapid advances in information technology. As Deputy Secretary Work has stated, innovators now encounter "fast followers" (Freedburg, 2015). Accordingly, the operational implications of longer schedules have indeed become more important. And the DoD's leadership recognizes that importance. A number of organizations have recently been created in order to field new capabilities more quickly.

In short, major changes in international military affairs and recent DoD emphasis has created a new environment, in which an ability to understand the schedule consequences of program strategies is especially important.

Accordingly, we discuss the matter of acquisition schedules within the context of contemporary military affairs below. Then we address schedule estimating tools and schedule estimating methods. In the section following that, we take the JCIDS instruction literally, and essay an abstract discussion of cost-time-performance trade-offs.

One promising variable for schedule estimating relationships is system performance, which is discussed next—primarily in the context of tactical fighters, the F-35 in particular.

The section titled Toward Explaining the Time Curve[1] is about empirical models for estimating schedules. One likely schedule driver is requirements growth. In a following section, we offer a narrative concerning the requirements growth that occurred from CALF (Common Affordable Lightweight Fighter) to JSF (Joint Strike Fighter, F-35). Finally, we offer concluding comments and thoughts about a research agenda aimed at making more realistic schedule estimating tools available to our acquisition professionals.

Introduction

Why Schedules Are Important

> "The fact is that we are slower than the bad guys."
>
> —Esti Peshin, Director of Cyber Programs for Israel Aerospace Industries (quoted in Sternstein, 2015).

Cost and schedule are critical variables in any acquisition program. And the DoD has indeed committed serious efforts over an extended period of time to develop the means for realistic acquisition cost estimates.

There are at least five good reasons for increased focus on realistic schedule estimates:

- Planning to pay for force modernization in an era of restrained budgets, especially in the next decade;
- Longer times to field new capabilities (absolute and relative);
- Rapid fielding initiatives throughout the DoD; and

[1] That is, the upward trend in time needed to field new systems.

- Current marching orders, including the Air Force "should-schedule" initiative.

(Apparently) Looming Budget Squeeze

There's a budget squeeze for the DoD expected in the 2020s, driven largely by modernization programs. This has been well documented by experts both inside and outside the government (e.g., Congressional Research Service [Gertler, 2015]; Center for Strategic and International Studies [Harrison, 2016]).

This is especially difficult for the Air Force, whose top-3 priority acquisition programs account for almost all of resources expected to be available for modernization. For example, these (KC-46, F-35, Long-Range Strike Bomber), plus C-130J and unmanned aircraft account for 99% of the service's aircraft acquisition budget for FY16 (Gertler, 2015, Summary, 1), with the situation continuing throughout the 2020s.

Furthermore, there's every reason to expect budget squeezes to continue well into the future. The entitlement bills are now coming due—expected to account for about 15% of GDP in 2026. Net interest on the federal debt is estimated at 3%; "discretionary" expenditures for about 5%, about half of which is estimated for defense (Congressional Budget Office [CBO], 2016, esp. pp. 66, 84). Revenues are estimated at about 18% of GDP (CBO, 2016, p. 92), with long-term deficits of about 5% of GDP. This means major pressure on the "discretionary" categories—defense especially.

Therefore, some preplanning and painful prioritizing seems both necessary and inevitable. A number of options are available, none of them pleasant (Gertler, 2015; Hale, 2016; Harrison, 2016). And it's reasonable to expect that the longer necessary decisions are postponed, the range of alternatives available will continue to narrow. But without reasonably good program schedule estimates, any early decision loses credibility and usefulness.

Schedules Have Become More Important: Time to Deliver New Systems Is Increasing

"(Acquisition) lead time in the U.S. is too long," according to LTG Arthur Trudeau, Army Chief of Research and Development (1958, quoted in Peck & Scherer, 1962, p. 425). But lead times are getting longer. For example, the F-35 concept is generally regarded as being formed in July 1993, with the creation of the Joint Advanced Strike Technology (JAST) program (Defense Science Board [DSB], 1994, ES-1). The F-35B, for example, was declared operational on July 31, 2015 (USMC, 2015), meaning a lead time of 22 years.

This is illustrated in Figure 1. One implication is that the widely-mentioned 2030 IOC[2] of a next-generation fighter aircraft appears fanciful at best. If source selection for a sixth-generation fighter aircraft occurs in 2020 (optimistic), we can expect an IOC some time past the middle of the 2030s.

Schedules Are Becoming More Important in an Era of Faster Followers

As Robert Work, Deputy Secretary of Defense, put it, we're in an era of "fast followers" in military affairs (Freedburg, 2015). And there's excellent reason this problem is

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[2] Fielding a new fighter in 2030 has been advocated as an operational "requirement" (Gen Mike Hostage, quoted in Mehta, 2012) and also to alleviate fighter aircraft shortfalls (Tirpak, 2009, 38).

getting worse; as an Air Force flag officer put it, “Emerging threats’ timelines are decreasing. (Our) acquisition times are increasing.”[3]

The current schedule difficulty is made more acute due to the adaptiveness of our rivals. Given especially the extended period of development for many U.S. weapon systems, those countermeasures have time to development. Thus, for example, potential adversaries have seriously pursued countermeasures to U.S. stealth fighters (e.g., Fulghum, 2012; Keller, 2016; Majumdar, 2014; Sweetman, 2015c, 2015d). The principal enabling technology is rapid computing, which can combine fragmentary sensor information into a unified picture (Clark, 2014). All in all, stealth may indeed be overrated (as the CNO, Admiral Jonathan Greenert, stated, quoted in Hasik, 2016a).

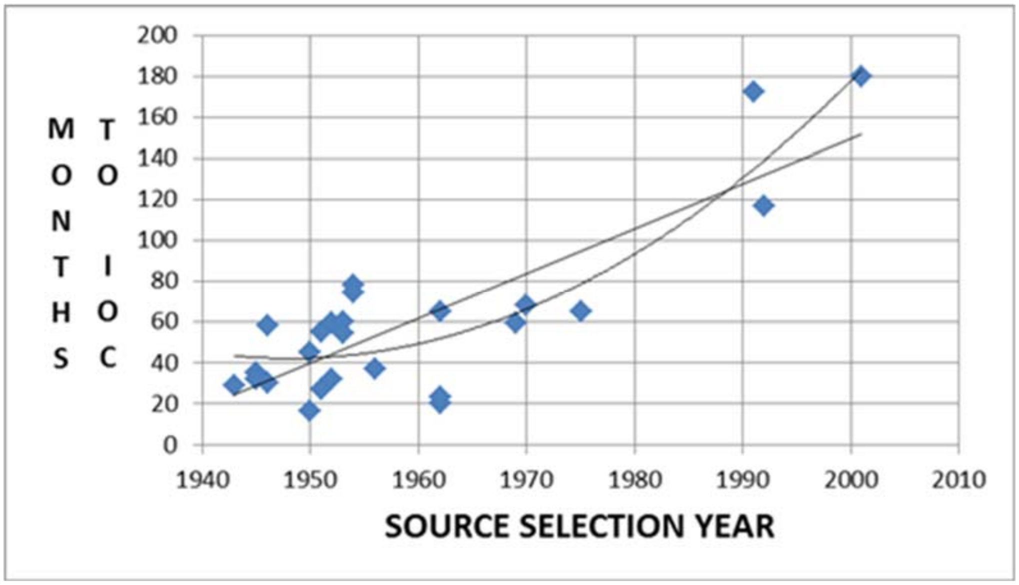

Figure 1. The Time Curve in Months to IOC vs. Source Selection Year for Tactical Fighters
(expanded from Blickstein et al., 2011, Table 4.5, p. 48)

This is relevant to schedules. It’s possible that a stealthy aircraft, if delayed long enough, can operate only at considerably reduced effectiveness (Franck et al., 2012, p. 68). Therefore, it’s important that new capabilities, and upgrades, be fielded in a timely manner and that planners have a realistic estimate of how long it will take to field new combat capabilities.

Current Marching Orders Regarding Schedules

Recognizing the problems discussed above, the services and the DoD have undertaken initiatives to field new capabilities sooner. These have included the Air Force Office of Rapid Capabilities (RCO) and OSD’s Strategic Capabilities Office (SCO). The RCO began in 2003; its basic purpose is to accomplish “expedited and operationally focused concept-through-fielding activities to support immediate and near-term needs” (Clark &

[3] Observation offered at a symposium in May 2015, not for attribution.

Freedburg, 2016; U.S. Air Force, 2009). In addition, the Navy has proposed an office which will "be something that closely mirrors the Air Force RCO," according to the Navy's senior acquisition officer (Clark, 2016).

The SCO originated in 2012. Its basic purpose is "to re-imagine existing DoD and intelligence community and commercial systems by giving them new roles and game-changing capabilities to confound potential enemies (with) the emphasis … on rapidity of fielding" (Carter, 2016; Clark & Freedburg, 2016). In addition, an ongoing legislative initiative, associated with Rep. Mac Thornberry (R-TX), is intended to streamline acquisition processes (Hasik, 2016b).

Also, Secretary of the Air Force Deborah Lee James (2015) has begun the "should schedule" initiative: "The previous incentive focused on cost, now we'd like to target delivery time. … If we can collectively beat the historical developmental schedules and reward the behavior in government and industry that speeds things up, we have a real chance to make a difference."

To implement the "should schedule," Secretary James proposes, *inter alia*, that schedule be a major factor in source selections: "If an industry partner can propose a solution that credibly offers a way to accelerate successful EMD, then that company would have a competitive advantage for the award" (James, 2015).

This sounds good, but let's consider a future acquisition scenario. Suppose a major acquisition program involves proposals, from Firms A and B, and that Firm A wins the competition. Let's further suppose that estimated schedule is a major factor in that decision. Finally suppose this particular program involves a long-term, high-value, winner-take-all contract—like many competitions these days. And it's a safe bet that Firm B will protest.[4] While "any accelerated EMD plan would need to survive a detailed scrub by independent engineers" (James, 2015), that might well not be enough. At minimum, those proposed schedules should also survive a detailed scrub by the GAO.

On Schedule Estimating Methods

Program schedule time can be analyzed and forecast according to the following (non-inclusive) menu:

- Schedule length arising from an orderly relationship involving key variables;
- Schedule as a result of a series of management decisions intended to produce the best outcome with respect to performance, cost and time;
- Schedule resulting from the interactions among a set of tasks needed to complete the program.

We know quite a bit about the last item—through, for example, Program Evaluation and Review Technique, Critical Path Method and Gantt Charts (Blanchard & Fabrycky, 2006, esp. Chap. 11; Defense Systems Management College [DSMC], 2001).

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[4] The protest may or may not have a convincing rationale. See, for example, Bill Sweetman's (2015e) analysis of the Boeing-Lockheed Martin protest of the LRSB source selection.

We know less about the second but can learn more through case studies (as discussed below), and official post-mortems like those conducted for cost problems by the OSD's Office of Program Assessment and Root Cause Analysis (PARCA) office.[5]

We know some things about the first, through descriptive analyses such as illustrated in Figure 1. And we can do more to improve empirical methods. Along those lines, the discussion below provides an interesting empirical analysis of schedule lengths.

It's possible to formulate an orderly-relations approach in a manner similar to formulating Cost Estimating Relationships. We offer the term "Schedule Estimating Relationships." We already have a fair number of possibilities for key explanatory variables. These include the following:

- risk reduction measures (including those prior to source selection);
- contract type;
- technical maturity of subsystems and components;
- requirements growth (or not);
- "complexity" and "density"; and
- funding instability (or not).

Worth noting is that some (perhaps all) items on this list could also apply to program cost estimation.

There's nothing original here; the first four items have been publicly cited as lessons learned and applied to the LRSB program (Butler, 2015; Seligman et al., 2015; Sweetman, 2015d; Tirpak, 2015). In addition, below, we discuss requirements growth in the F-35 program.

"Complexity" is suggested as an explanatory variable by a particularly interesting comment by a senior DoD official: "Our complexity reach exceeds our engineering grasp."[6] One plausible metric for complexity is lines of code (virtual complexity perhaps). For example, Hallion (1990) reports 64,000 lines of code in the F-15A and 2.4 million lines in the F-15E. Lines of code in the F-35 vary with source and date. A 2014 CRS report estimates F-35 software as containing approximately 29 million lines of code and still growing (Gertler, 2014, p. 14).

In addition to virtual complexity, we could consider "density," indicating physical complexity. Density is "how tightly systems and equipment are placed within a hull structure" (Grant, 2008). There is other interesting research on "density" as a cost driver for warships (e.g., Terwilliger, 2015).

[5] In fact, *post-mortem* analysis of schedules arguably fits directly within the PARCA charter. (http://www.acq.osd.mil/parca/performance-assessments.shtml).
[6] Ninth Annual Acquisition Research Symposium, May 2012, Monterey, CA. Comment understood as not for attribution.

Schedule Estimating Goals

We think that something like the current structure for cost estimates is a useful analog in thinking about a similar structure for schedule estimates. This is illustrated in Figure 2.

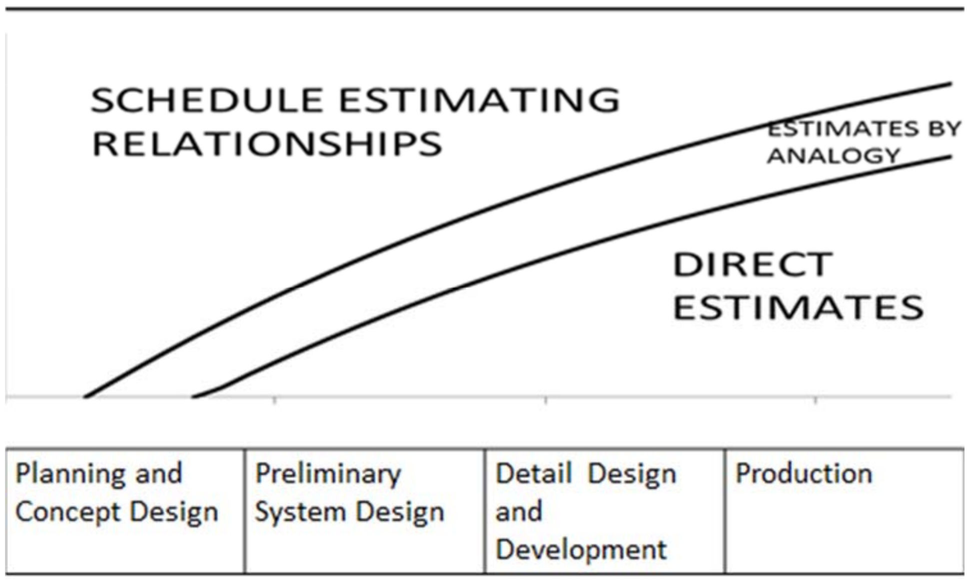

Figure 2. Schedule Estimation by Program Phase
(adapted from Blanchard & Frabrycky, 2006, Figure 17.9, p. 595)
Note. Source draft referred to cost estimation by program phase.

In that vein, a comprehensive schedule estimating repertoire would include the following:

- macro-level, statistical methods to do those estimates in the early stages of the program (ex ante),
- more specific methods to update schedule estimates during the program (in media res), and
- methods for explaining the results of events and decisions previously in the program (ex post).

For estimates done early in the program, we think "Schedule Estimating Relationships" featuring historically important schedule drivers are promising. They can provide preliminary estimates of acquisition schedules to inform concept and requirements determination. They could also serve as an independent check of scheduling aspects of bidders' proposals.

During program execution, it's highly desirable for program managers to have the means to update schedule estimates. To a considerable extent these already exist, as discussed, for example, in the DAU's *Scheduling Guide for Program Managers* (DSMC, 2001). A number of tools (discussed above) are available to program managers and their staffs (Blanchard & Fabrycky, 2006, esp. Chaps. 11 & 18).

Finally, schedule analysis and prediction methods can usefully support after-the-fact (ex post) analyses of program successes and difficulties. Such tools could enable schedule analyses similar to those now conducted by the OSD's Root Cause Analysis office for selected programs with cost problems.

Cost–Performance–Schedule Trade-Offs

Schedules arise from trades (perhaps implicit) among cost, schedule and performance. And "making … effective *cost, performance, schedule*, and quantity trade-offs" (emphasis added) is a major theme of the JCS directive for the Joint Capabilities Integration and Development System (JCIDS; CJCS, 2015).

We know a fair amount about the structure of cost, performance, and schedule trade-offs, but there's more worth finding out. As one report put it, "the literature linking cost, performance, and schedule is by no means abundant. This is due in large part to the sheer complexity of the interrelations between performance characteristics and technical specifications, as well as the unique missions … systems" (Voltz, 1992, p. 13). In this section, we offer a preliminary explanation of those trade-offs taken two at a time: Cost and Performance; Cost and Schedule; Performance and Schedule.

Cost and Performance

Of these three, we probably know most about Cost vs. Performance. Basically, we expect to pay more to acquire higher performance. Figure 3 shows a notional trade-off with effects of technical progress.

That relationship has been investigated in a number of empirical studies. One of those (Hildebrandt & Sze, 1986, p. 15) led to the following cost-performance relationship (in log-log form) shown below. This is the result of a regression analysis of a data base of 66 fighter and attack aircraft with first flights from 1950 (F-89) to 1979 (F/A-18).

$$\ln CAC = 1.99 + \ln{*}P + 1.31\ln{*}ASP - .31\ln R - .03T - .50{*}ATTACK - .89{*}M0D + b_i{*}\ln Y, \qquad (1)$$

where CAC is cumulative average cost; P is resource price levels (primarily labor and materials); ASP is an aircraft performance index; R is production rate; T is year of first flight; ATTACK is dummy variable (1 for attack aircraft, 0 otherwise); MOD is a dummy variable for aircraft models that are modifications or upgrades of an existing aircraft type; bi is the relevant learning curve parameter; and Y is cumulative production. Franck (1992) used the same data to infer patterns of cost-performance design choices.

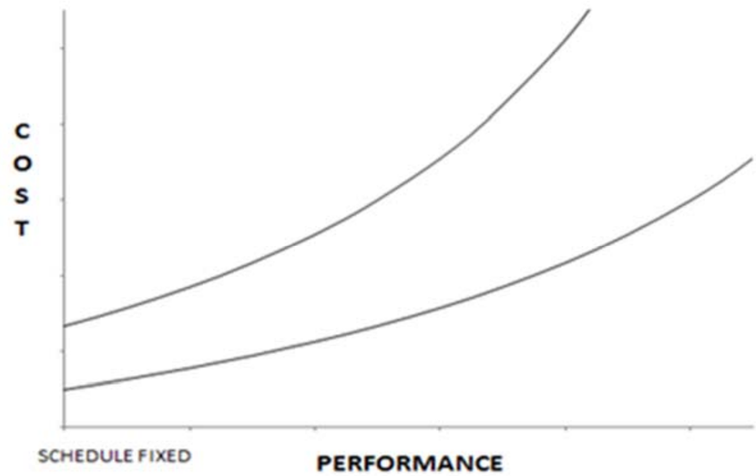

Figure 3. Cost vs. Performance Trade-Off
(adapted from Gansler, 1987, p. K-8; Sullivan, 1981)

The first-flight variable is intended to capture the effects of technical progress. All other things equal, we expect to pay less for a given level of performance with improvements in technology. This is illustrated in Figure 3, which includes effects of technical progress. As previously stated, as performance increases, so does cost. However advancing technology shifts the cost-performance curve down and to the right (lessening to cost of any given level of performance).

Program Schedule and Cost

Effect of development time on program cost is somewhat ambiguous. Keeping a team in place longer means greater overhead expenses (sometimes called the “standing army” effect). But shorter development times can mean less chance to develop technology and sort among alternative approaches and incurring the costs associated with cascading effects of wrong turns.

These seem, in general, to be countervailing effects. Less time means less overhead cost over the life of the program. More time means better chances to avoid pitfalls and manage risk. In theory, the best course of action is reached by balancing increases in overhead (indirect) cost with direct program cost. This is shown in Figure 4.

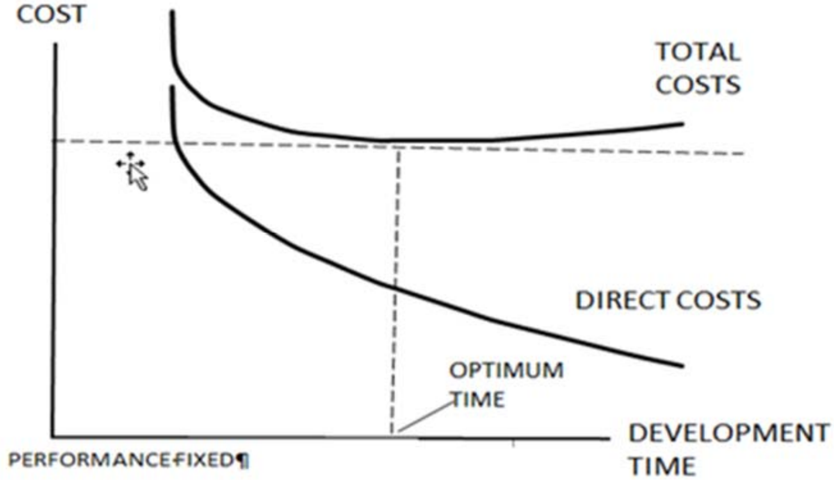

Figure 4. Total Cost Analysis for Selecting Optimum Program Duration
(adapted from DSMC, 2001, p. 60; Zschau, 1969, pp. 28–30)

This sketches nicely, but solving the implied problem is more complicated. For example, not all relevant costs are internal to the acquisition program itself. As the DSMC *Scheduling Guide* points out, “Each month added to the development and production of a new … system tends to reduce by 1 month the operational life of the product” (DSMC, 2001, p. 61). This suggests that monetized effects of fielding delay should be added to total costs—a difficult task.

Nonetheless, those costs of delay can be all too real and multifaceted, as illustrated by the F-35 program. The effects included a projected shortfall of tactical fighters in both the Air Force and Navy (Tirpak, 2010; Trimble, 2010). To help bridge that gap, it was necessary to keep the older “legacy” aircraft in service for longer than originally planned—and consequently spend more money than originally planned to retard their rate of obsolescence. For example, the U.S. Air Force has been obliged to devote considerable resources to upgrading its “legacy” fourth-generation systems and to extending their operational lives (GAO, 2012). Overall, “the failure of the so-called fifth-generation fighters … to arrive on time and on cost has cascading effects throughout U.S. and allied fighter forces” (Sweetman, 2012).

Schedule and Performance

A notional representation of system performance vs. program time appears in Figure 5. The figure implies that increasing program time allows for a more considered approach that permits better decisions. However, increases in indirect cost caused by a longer program crowd out resources directly useful for system development. And beyond some point, the slope of the Performance vs. Time curve goes negative.

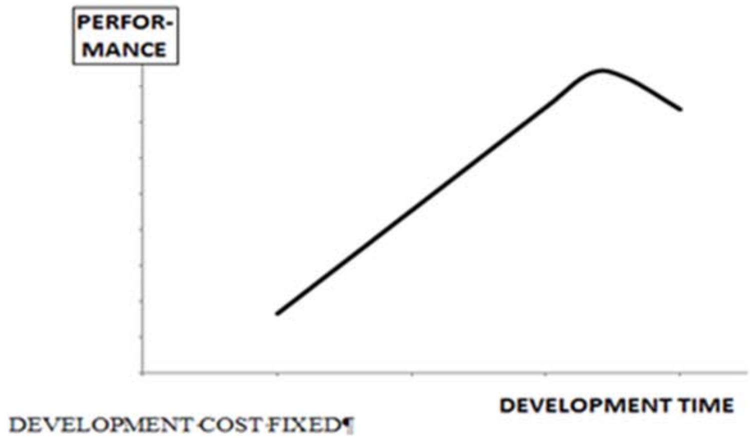

Figure 5. Performance vs. Development Time Trade-Off
(adapted from Zschau, 1969, pp. 28–30)

While certainly understandable in the abstract, there are some difficulties with this trade-off in practice. Among other things, development programs that proceed with a strictly fixed budget are very rare, if not nonexistent. This limits opportunities to develop a model grounded in actual experience.

The Concurrency Issue

Program "concurrency" is generally understood to involve beginning production prior to completion of development testing (DoD, 2015, p. 46), or more broadly as "combining or overlapping phases" ("Concurrency," n.d.).

Concurrency is frequently cited as a "high risk strategy that often results in performance shortfalls, unexpected cost increases, schedule delays, and test problems" (GAO, 2012). On the other hand, Goure (2015) noted "a number of reasons to pursue concurrency," including early identification of production problems and faster fielding of new hardware.

One very interesting study suggests an optimum level of concurrency (from the perspective of cost). However, the authors did not find strong empirical evidence to support that hypothesis (Birchler et al., 2011, p. 252). Nonetheless, some form of dynamic, simultaneous-equation model might prove useful.

Measuring Performance

Metrics for cost and schedule time are generally well understand. Metrics for performance are much less definite. Generally system "performance" is reported as a vector. For tactical fighters, the elements of the vector are characteristics such as maximum speed, service ceiling, thrust-to-weight ratio, combat range, weapons carriage, and Radar Cross Section (RCS). One noteworthy effort to develop performance indices (scalar measures) for a variety of combat system types was undertaken by the Analytic Sciences Corporation (ANSER). This occurred mostly in the 1980s and described as the TASCFORM method (Regan & Voigt, 1988).

Within that overall project, the TASCFORM-Air model of combat capability was intended to assess tactical fighters, attack helicopters, and bombers in various conventional missions (Regan & Voigt, 1988, p. 1-1). Tactical aircraft were assessed in the context air-to-air ("air combat") and "surface attack" against both land and maritime targets (p. 2-2). The basic intent of TASCFORM-Air was to systematize observable technical features and combine those with judgments of air combat experts to provide (scalar) indices of fighter capability in several operational contexts.

The capability measures applied directly to individual aircraft are organized in a hierarchy:

- Weapon Performance (WP, a function of weapons carriage, range, maneuverability and speed);
- Weapon System Performance (WSP, WP plus target acquisition, susceptibility to countermeasures, weapon enhancements, navigation and survivability)
- Adjusted Weapon System Performance (AWSP, WSP plus “obsolescence” and sortie rate; p. 2-4).

So, how does the F-35 performance look relative to fourth-generation fighters? A comparison of the aircraft types in the Weapons Performance dimensions (which emphasize payload, range, maneuverability, and speed) shows there’s not much difference.

- Hard points: F-35 has a comparable number of weapons hard points relative to the F-18 and F-16 but much fewer in stealth mode.
- Max Speed: all three aircraft are all comparable.
- Ferry Range is comparable, if F-35 has external tanks.
- There’s a Combat Range advantage for the F-35 when operating in a high-high-high profile, compared with range in a high-low-high profile for the fourth-generation fighters.
- Maneuverability: Thrust-to-weight ratio, max Gs, and wing loadings are comparable for F-16, F-18, and F-35.
- Sortie Rate: not yet determined. The F-35 is still maturing.
- Survivability: favors stealthy aircraft, but nonetheless subject to countermeasures (discussed above).

Force capability is generally presented as numbers and types of systems. Force capability indices are also discussed in TASCFORM (pp. 2-4, 2-30–2-36), in which force capability is assumed to be the sum of individual performance (by tail number). These measures do not fully address force effectiveness as a function of networking and shared situational awareness.

The fifth-generation fighter advocates have a new perspective on system and force capabilities. New aircraft models such as the F-22 and F-35 are seen as disruptive innovations. Within this perspective, the operational capabilities of the fifth generation are due to the combination (synergy perhaps) of airframe characteristics and “ability to work within and interact with a broad array of networked systems” (Deptula, 2011; Space Daily Staff, 2006).

Moreover, fifth-generation characteristics, especially stealth, increase the proportion of resources devoted to offensive air operations. Fifth-generation aircraft likely need fewer fighter sorties to support penetration of advanced and integrated air defenses, and fewer tanker sorties (due to smaller strike packages).

Regardless of one’s opinion of fifth-generation performance advantages, it’s hard to avoid the conclusion that a credible method of measuring system (and force) performance should account for the advantages of stealth, shared battlefield awareness, and networked operations.

F-35: From CALF TO JSF[7]

The Lockheed Martin F-35 Joint Strike Fighter (JSF, Lightning II) is a single seat, single engine, fifth-generation multirole fighter designed to perform ground attack, reconnaisance, and air defense missions while in stealthy operation. It was originally visualized as a relatively affordable strike fighter available in three largely common versions for the Air Force, Marines, and Navy. It didn't work out that way.

Then-Major General Christopher Bogdan (JSF Program Executive Officer designate) commented that the F-35 "is not a single program (but rather) three separate airplane programs (with) common avionics and a common engine." He also stressed the difficulties involved in reaching agreement on decision-making. In his words, "It's hard enough to get one service to answer questions about requirements. Imagine three services, eight partners, and two FMS customers" (Bogdan, 2012).

All three models are designed for limited supersonic operation, and to carry their primary weapons internally, to preserve their stealth characteristics. Although physical differences arose from methods of takeoff and landing, requirements were also driven by different operational needs.

The F-35A was a replacement for the F-16, the A-10, and perhaps the F-15 fighter. In addition, it is intended to complement the F-22 air superiority fighter. The Air Force sought an advanced attack aircraft with stealth, advanced avionics, and low life-cycle operating costs providing improved range, speed, and appreciable weapons load capacity.

The F-35B is a short takeoff and vertical landing aircraft (STOVL) acquired to replace its AV-8B Harrier and its F/A-18A/B/C/D strike fighters. It was designed to operate from forward battlefields, helicopter carriers, and as a "jump jet" from smaller conventional carriers. The F-35C (CV) chosen by the U.S. Navy resembled the Air Force's F-35A but was modified for carrier operations. It is intended to replace earlier versions of the F/A-18.

Joint and International Nature

At the time of JSF conception, there was a clear preference at the highest levels of the DoD for joint projects. Typically, the rationale for jointness is that a largely joint project lessens costs of developing, procuring, and operating and supporting some large number of separate aircraft designs with similar (but not necessarily identical) requirements.

A study by the RAND Corporation undertook to examine this issue (Lorell et al., 2013), which focused on the costs of jointness. The critical finding is

> the need to accommodate different service requirements in a single design or common design family leads to greater program complexity, increased technical risk, and common functionality … beyond that needed for some variants, potentially leading to higher overall cost, despite the efficiencies (of common design). (Lorell et al., 2013, iii)

[7] This section relies in part on background information from Aboulafia (2015) and Gertler (2014). Also we found the Wikipedia article on the F-35 to be a good source for those seeking basic information on the program ("Lockheed Martin F-35 Lightning II," n.d.).

The F-35 won the DoD source selection, with an industry team of Lockheed, Northrop Grumman, BAE Systems, and Pratt & Whitney. (Aboulafia, 2015, identified the F-35 suppliers in more detail.)

From the earliest days of the JSF project, the Office of the Secretary of Defense stressed international participation. The UK joined the JSF project as a Level 1 Full Collaborative Partner. There were five (Level II) Associate Partners and three (Level III) Informed Partners in the Systems Development and Demonstration Phase (Schreiber, 2002, p. 164).

History and Antecedents

Defense procurement funding fell sharply in the early 1990s, implementing the Bottom Up Review recommendations—ending such programs as the NATF (Naval Advanced Tactical Fighter) and the A-12/ATA. Fearing loss of domestic military aircraft design skills, the DoD undertook a series of largely unsuccessful programs. This effort include support for design of advanced technology aircraft available for production.

The list of aircraft concepts not leading to production includes the following (e.g., Aboulafia, 2015, esp. pp. 10–11):

- A-X/A/F-X, a Navy-dominated joint program was canceled due to the A-12's high cost, and by the 1993 appearance F/A-18E/F (Super Hornet).
- ASTOVL/SSF (Advanced STOVL/STOVL Strike Fighter) was an ARPA project intended to develop a supersonic AV-8B Harrier successor. NASA and the UK both participated in this effort. It was merged by Congress with JAST in mid-1994.
- CALF (Common Affordable Lightweight Fighter) was the formal name for DARPA's ASTOVL project that included a conventional take-off design capability. Sometimes known as the X-32, CALF was merged into JAST in November 1994.
- JAF (Joint Attack Fighter) explored the same ideas as JAST, as was also true of the JSSA, the Joint Stealth Strike Attack Aircraft.
- MRF (Multi-Role Fighter) was a Navy/Air force program designed to produce a follow-on aircraft for the F-16, F/A-18 and several other legacy planes. It was sidetracked by the appearance of the F/A-18E/F (Super Hornet).

JAST/JSF

The F-35 Joint Strike Fighter emerged from the Joint Advanced Strike Technology Program (JAST). However, JAST's original goal was to develop technologies for advanced strike aircraft (DSB, 1994). It happened that JAST's plans to fund several concept demonstrator aircraft in 1996 coincided with ASTOVL's planned timing of the start of its Phase III (full-scale flight demonstration). The managements of both programs concluded that it would be logical to make JAST the U.S. military service sponsor for the flight demonstration phase of ASTOVL. In any case, FY95 budget legislation directed an immediate merger of ASTOVL into JAST (DoD, JSF History, 2015).

In early 1997, Lockheed Martin and Boeing were selected to develop flying airframes for the concept demonstration phase. They were designated X-32 (Boeing) and X-35 (Lockheed Martin), respectively, with evaluations between September 2000 and August 2001. On October 26, 2001, the Lockheed Martin team was announced as the winner, after which the program transitioned to the JSF System Development and Demonstration (SDD) phase (Aboulafia, 2015, esp. pp. 11–12).

Cost and Scheduling Problems

Few new weapon systems have earned such a widespread reputation for problems encountered in the design and development stages as the F-35. A few comments are useful here. Early development problems in many new products were followed by highly effective operational performance. The C-17 is one example (Franck et al., 2012). But the F-35 involved much more difficult design and development problems (Blickstein et al., 2011, esp. pp. 42, 49).

The RAND Corporation and others reviewed the Joint Strike Fighter and provided a root cause analysis of its cost problems. The RAND report identified "in some measure" an overly optimistic government estimate of the influence of acquisition reform and "produceability initiatives" as responsible for underestimates of future procurement cost growth. When combined with a perceived strong need for an improved F-16 replacement, the OSD proved willing to begin "a technologically complex, highly concurrent F-35 program." The end results included schedule slippage and cost growth that resulted in a Nunn-McCurdy breach (e.g., Rutherford, 2010).

Explaining the Time Curve

In this section, empirical models are discussed that focus on the key variable: Months from Initial Award to IOC (or Time to IOC) for fighter aircraft. As shown previously, this variable has increased with later initial award years for fighter aircraft.

In this empirical analysis, contract-level data contained in Selected Acquisition Reports (SARs) or the F/A-18E/F, F-22, and F-35 (and, where possible the Air Force F-35A) is emphasized. For each published SAR, generally on December 31, both program and contract level data are included. Because each SAR for fighter aircraft contain data for two or more contracts (both airframe system and engine), data at this level not only increases the size of the data set but also permits inclusion of contract type, changes in the target cost, years elapsed since time of contract award, and contract variance. Contract variance information (not required for Firm Fixed Price contracts) includes both cost and schedule variance. The former provides information on the difference between the planned and actual contract cost, the latter on the difference between the planned work performed and scheduled. (Future analysis will extend this work to include program-level data including the various program-level variances.)

Examination of the available data indicates that complex interactions among the relevant variables complicates the traditional regression analysis view of explanatory variables affecting the dependent variable. Our analysis includes both explanation and association. Including association variables provides insight into the strength of the relationships between these variables and the dependent variable (other variables held constant).

We are also investigating professional-judgment measures of fighter effectiveness for fighters, which would increase the regressions' explanatory power. One variable obtained from non-SAR sources, included in the current analysis, is the percent of an aircraft's structural weight consisting of composites.

To understand the empirical analysis, an influence diagram appears in Figure 6—in the form of path analysis in which *Time to IOC* is related to contract-specific cost variance and other variables. In turn, current minus initial target cost is related to contract variance data, contract type, and several other variables. We also identify the expected signs of the regression coefficients when possible.

Broadly speaking, Figure 6 displays those variables that directly related to *Months from Initial Contract Award to IOC,* namely *Contract Current—Initial Target Price, Program Year, SAR Year—Contract Award Year*, and C*omposites* as a *Percent of AC Structure Weight.* There are also indirect relationships between certain explanatory variables and time to IOC. This occurs through these variables' direct relationship with [*Contract Current—Initial Target Price*]. The variables with an indirect relationship with time to IOC are *Program Year, [SAR Year—Contract Award Year], [Contract Cost Variance and Contract Schedule Variance], Aircraft MDS,* and *Contract Type.*

The only variables with uncertain sign of regression coefficients are Aircraft MDS and Contract Type. It is likely easiest to understand this diagram through a discussion of the regression results. First, Figure 6 shows the direct relationship between explanatory variables and Time to IOC.

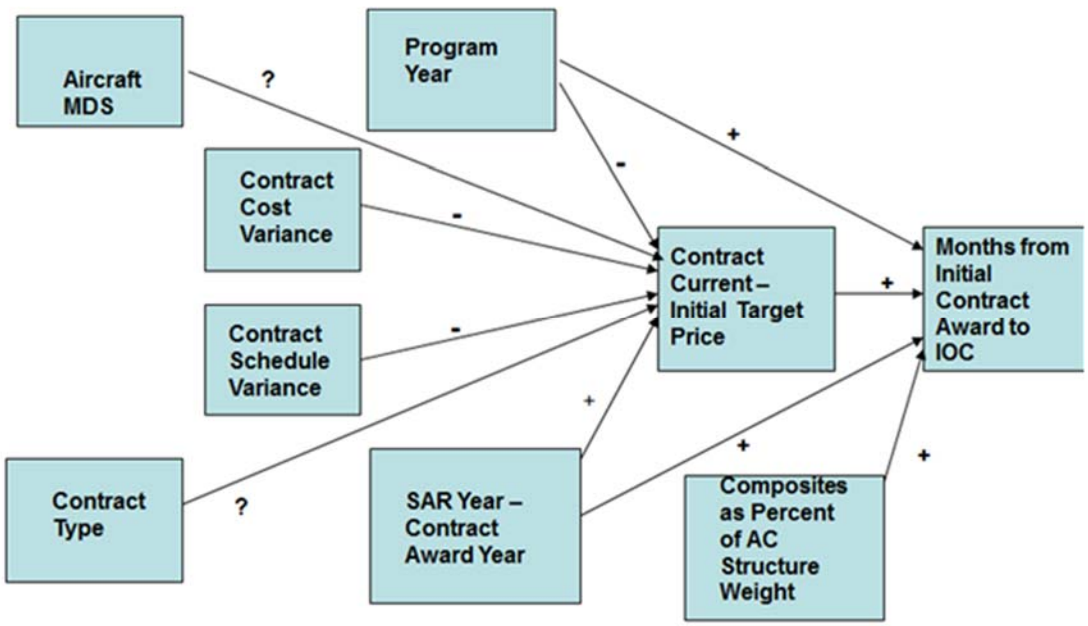

Figure 6. Structure of the Regression Model

The results in Table 1 show all variables being statistically significant given the hypothesized signs of the coefficients in the figure. When the current target minus the initial target price increases, this likely means that a specification change occurred. One would expect specification change to be associated with a longer Time to IOC. As *Program Year* increases, this is likely related to a longer program length. In turn, this is likely related to an increase in Time to IOC. An increase in *[SAR Year—Contract$_i$ Award Year]* indicates that a schedule delay is likely.

The most interesting independent variable may be *[Composites as a Percent of AC Structural Weight].* We show that as this increases, which is exactly what occurred when shifting from the F/A-18E/F to the F-22 to the F-35 programs, the dependent variable increases. It is known that working with composite materials is more complex than traditional materials, and as result, can be expected to increase the length of the program to IOC.

Table 1. Direct Effects for Months-to-IOC Regression

Explanatory Variable	Coefficient	t-statistic
(Constant)	50.409	12.478
Contract Current - Initial Target Price ($B)	1.309	2.880
Program Year	2.030	10.015
SAR Year - ContractAward Year	0.986	3.853
Composites as Percent of Structural Weight	3.051	21.242
FFP Contract	12.450	5.920
Dependent Variable: Months from Initial Contract Award to IOC		
R^2 = 0.846; N = 164		

We turn now to the indirect effects regression. We have seen that *[Contract$_i$ Current Target—Initial Target Price]* has a positive direct relationship with the key dependent variable. But there are also variables that have a direct relationship *with [Contract$_i$ Current Target—Initial Target Price],* and, therefore, an indirect relationship *with [Months from Initial Contract Award to IOC].* Table 2 displays this set of regression results.

Table 2. Indirect Effects in the Regression Model

Explanatory Variable	Coefficient	t-statistic
(Constant)	3.222	3.941
Cumulative Contract Cost Variance	-4.810	-4.725
Cumulative Contract Schedule Variance	-6.072	-3.339
Program Year	-0.213	-3.934
SAR Year - Contract Award Year	0.168	3.506
F-35	-1.333	-3.867
F/A-18E/F	-1.979	-4.257
CPAF Contract	-0.860	-2.019
Dependent Variable: Contract Current Target - Initial Target Price		
R^2 = 0.665; N = 110; Financial Variables, $B		

The *Cumulative Contract Cost* and *Schedule Variance* coefficients are interesting. Contract Cost Variance Budgeted Cost of Work Performed minus Actual Cost of Work Performed; and Schedule Cost Variance equals Budgeted Cost of Work Performed minus Budgeted Cost of Work Scheduled. So, as these variables both increase, the extent to which the contractor is over budget and behind schedule decreases. Therefore, motivation to revise target price also decreases, consistent with the negative coefficients.

As *Program Year* increases, specifications become more settled, and target price revisions are less likely, consistent with the negative coefficient. However, as contracts become longer, requirement and specification changes become more likely.

One advantage of employing both direct and indirect modeling is that one can more effectively assess indirect effects of Aircraft MDS and Contract Type on Time to IOC. Both the F-35 and the F/A-18E/F are negatively related to *[Contract$_i$ Current Target—Initial Target Price].* For the F-35, this negative coefficient offsets somewhat the positive relationship between *[Contract$_i$ Current Target—Initial Target Price]* and *[Months from Initial Contract Award to IOC].* Finally, we find that CPAF contracts are negatively related to *[Contract$_i$*

Current Target—Initial Target Price], likely meaning smaller increase in specifications that, in turn, increase target price.

Draft Research Agenda

Acquisition schedules are becoming more important. Therefore, our final aim in this paper is to propose a research agenda aimed at producing more accurate schedule estimates, particularly in major defense acquisition programs.

Schedule Estimation Research: A Draft List of Questions and Tasks

1. What is the current state of schedule estimation and control? What's needed? Where are the gaps?
    - o Interview subject-matter experts regarding current state of schedule analysis, and areas for improvement.
2. How can operational performance metrics better capture contemporary operations?
    - o Update performance metrics for information-age warfare. Start with some existing method, such as TASCFORM.
3. What model(s) best capture the trade-offs among program cost and schedule, as well as operational capability of fielded equipment? Can those models give insight into "troubled programs," with difficulties in cost, schedule, and performance?
    - o Analyze previous case studies (e.g., from Kennedy School of Government) for insights into program schedule drivers.
    - o Publish new case studies dealing with contemporary acquisition programs, based, among other things, on a thorough analysis of relevant SARs.
4. What estimating relationships best capture time to field new hardware? What schedule drivers are generally most important?
    - o Based on available data, formulate and empirically test models with hypothesized schedule drivers.
    - o Formulate and test prediction markets for cost and schedule problems.
5. Is there a prediction market design that would produce useful information about impending cost and schedule difficulties?
    - o Design a prediction market for defense acquisition programs. Test it in an experimental setting.

While this is a very ambitious research program, it is readily decomposable into smaller projects. And that we were able to significantly advance the cost estimating state of the art suggests we can do the same with schedule estimation. Moreover, we'd likely find considerable insights from cost estimation methods useful for schedule estimation.

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