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In the Fullness of Time: Towards Realistic Acquisition Schedule Estimates

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Abstract

This paper continues a research agenda started in 2016 with an aim of more realistic acquisition program scheduling estimates, especially for the development (SSD) phase. This, our third look at the scheduling problem, starts with a discussion of scheduling data, and how that data could be applied to help the DoD address this challenge. This section includes ideas on how to use acquisition data for the scheduling problem. Next, we present a case study that is the result of field interviews with senior DoD leaders. Finally, we present a discussion on using the system performance as a metric.

Introduction

Weapons system development projects are infamous for exceeding time and cost limitations. Often the reaction to this notoriety is changes at the policy level of acquisition. However, the problem may well lie somewhere else. This paper, like the two preceding papers in this series, suggests we may well be “lookin’ … in all the wrong places” (to paraphrase an old country song[1]) for the causes, because the causes may well lie inside the project and therefore not be readily addressed by policy changes.

While cost, performance, and schedule are critical variables in any acquisition program, Congress, the media, and policymakers generally focus on cost, with little attention devoted to the issues of schedule. Moreover, although the DoD has engaged in significant efforts to develop methods for realistic acquisition cost estimates, it has paid considerably less attention to schedules—their estimates and execution. To emphasize the challenge of schedules, Figure 1 provides a macro level view of the schedule problem. Over the past 20 years, Major Defense Acquisition Programs (MDAPs), as reported in Selected Acquisition Reports (SARs), averaged schedule overruns of more than 24 months. Schedule overruns occur for many reasons and this study examines some of those reasons.

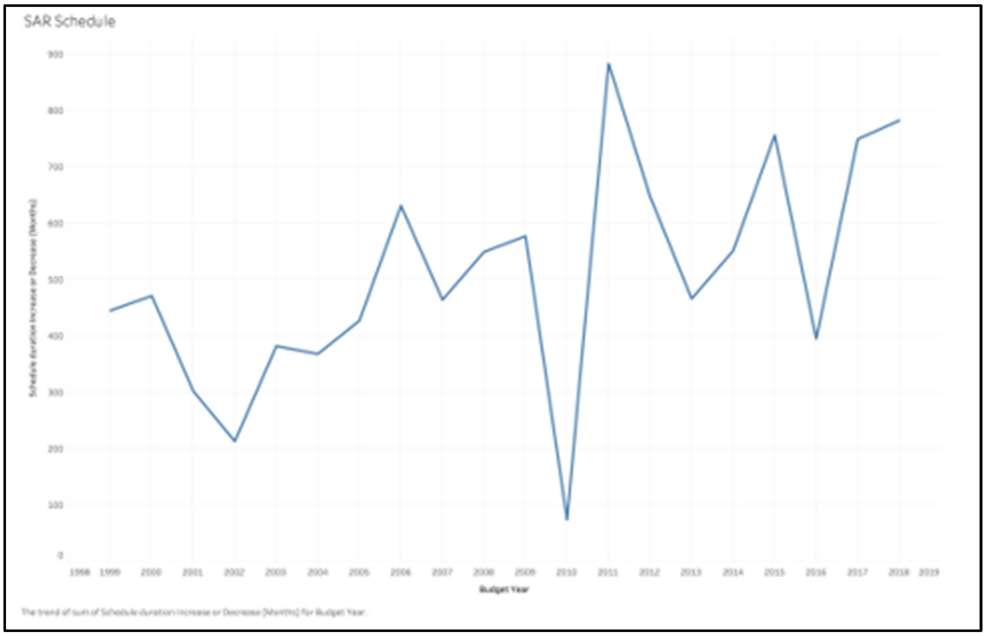

Figure 1. Sum of Schedule Overruns, 1998–2017 (Months)

We use a multi-faceted approach to examine weapons systems development scheduling to assess the current state and contributing causes of schedule estimating methodologies and suggest different ways to accomplish this difficult process. The overarching research question is as follows:

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[1] From the words to a song written by Wanda Mallette, Bob Morrison, and Patti Ryan, and recorded by American country music singer Johnny Lee in June 1980.

> *What analytical techniques and approaches can be applied to schedule development/analysis to increase the efficiency and effectiveness of schedule estimating and execution?*

As long ago as 1988, Morris and Hough were critical of the practice of project management:

> Curiously, despite the enormous attention project management and analysis have received over the years, the track record of projects is fundamentally poor, particularly for the larger and more difficult ones. Overruns are common. Many projects appear as failures, particularly in the public view. Projects are often completed late or over budget, do not perform in the way expected, involve severe strain on participating institutions or are cancelled prior to their completion after the expenditure of considerable sums of money.

In fact, project management in general, and DoD project management in particular, has been dealing with these problems described by Morris and Hough for decades. We hope to inform these problems because, "when problems persist, practitioners and scholars are getting something wrong" (Christensen & Bartman, 2016).

This paper is the third in a series of investigations into alternatives to the way we do schedule estimation today and builds on the research agenda proposed by Franck et al. in 2016 and furthered in Franck et al. in 2017 (Franck, Hildebrandt, & Udis, 2016; Franck, Hildebrandt, Pickar, & Udis, 2017). We start with a discussion of scheduling data, and how that data could be applied to help the DoD address this challenge, and how system dynamics can inform. Next, we present a case study that is the result of field interviews with senior DoD leaders. Finally, we present a discussion on using parametric analysis.

The Dynamics of Project Management

The concept of time in project management can be divided into two steps: estimating task duration and building the schedule. Both processes require technical expertise and management savvy. First the technical process of estimating the duration of the project task must be determined. Once duration is established, the management process of project sequencing and scheduling must be defined.

Estimating Activity Duration

Surprisingly, little information is available in the literature on the "how" to estimate the elements of a schedule—the task duration. While the major defense contractors have formal in-company processes, little formal literature is available on the specifics of task estimation. Further, most available information on estimating task duration is found in project management textbooks, but even then, the specifics are scarce.

The PMBOK (Project Management Body of Knowledge) lists five methods for estimating project activity duration. These methods include (Project Management Institute [PMI], 2017):

- Expert Judgment
- Alternatives Analysis
- Published Estimating Data
- Project Management Software
- Bottoms-up Estimating

Expert judgment acknowledges that technical and engineering experts should be able to estimate the effort necessary to accomplish tasks and translate those estimates to duration. This assumes the chosen experts have significant experience in the execution of those tasks, and are therefore competent to judge time required (Hughes, 1996).

Alternatives analysis recognizes that activities or tasks can be accomplished in different ways—alternatives. These different ways include defining different techniques, differing levels of resources, and using different machines.

Published estimates are databanks that gather resources measures. These measures include hourly rates by skill level, acknowledged production rates for various development, and manufacturing activities. In most cases, this data is available internal to the organization. However, there are data companies that track and report this data. An example is the IEEE-USA Salary & Benefits Survey. This data is often available for different locations in the United States as well as worldwide.

Project management software is not really an estimation method. Instead, it provides a means to identify and organize information necessary for resource estimates.

Finally, an engineering or bottoms-up estimate is a comprehensive schedule (and cost) process that starts at the work package level and aggregates costs to build a complete estimate. Bottoms-up estimates are necessary when schedule activities cannot be accurately estimated using another technique. As the name implies, bottoms-up estimates start at a level of activity or task that can be confidently estimated. The activities are then rolled-up to the required level. These estimates are extremely work intensive but are also the most accurate.

Other recognized methods include parametric techniques. A parametric or top-down estimate builds an activity estimate for the development project from historical data comparing variables through a statistical relationship. All the methods listed are used to estimate the length of time each of the activities or Work Breakdown Structure tasks lists. “Simply stated, the duration of an activity is the scope of the work (quantity) divided by a measure of productivity” (Hendrickson, Martinelli, & Rehak, 1987, p. 278).

Thus, activity duration estimation establishes the actual time required to complete discrete tasks in an overall project, while project scheduling fixes the start and end dates, as well as execution approaches of the project. Once the overall schedule is established, management activities driven by either time and/or resource constraints will determine the actual execution of the project (Schwindt & Zimmerman, 2015). The analogy that comes to mind is that of an orchestra. The individual instruments (and of course, the musicians) are the discrete tasks of the project. The orchestra leader is the project manager, and the music score is the “plan” the orchestra leader uses to execute the “project.” Building on this information, the next step in this effort is to identify schedule data that can be used to augment these estimating activities.

Schedule Data

While there is significant information available on DoD procurements, the overwhelming majority of that information is on cost. In order to effectively examine project schedules, we must be able to better understand those schedules. It is common knowledge that weapons system development projects overrun their schedules. However, we need to be able to determine what causes schedule overruns, as well as an actual measure of the development time.

Data for this research was obtained from the Defense Acquisition Management Information Retrieval (DAMIR) database, a repository for, *inter alia*, the DoD Selected

Acquisition Reports (SARs). The SAR is a summary of the acquisition data of selected Major Defense Acquisition Programs (MDAPs). Table 1 provides a list of delay factors, as well as maximum and minimum delays as reported in the SAR during the period 1997–2017.[2]

Table 1. Delay Factors, Maximum Delays, and Minimum Delays, 1997–2017

Delay Factor	# instances	Maximum Delay (months)	Minimum Delay (months)
Administrative changes to schedule including updates to APB, ADM changes, as well as changes resulting from Nunn-McCurdy processes and program restructuring	460	168	5
Technical	291	60	4
Testing delays	283	66	1
Delay in availability of key capabilities/facilities (launch vehicle/testing facilities/IOT&E units)	3	13	6
Budget/Funding Delays	52	43	1
Delays attributed to the Contractor	50		
Delays because of Rework	16	4	1
External events such as inflation, earthquakes, labor strikes, etc. (*Force Majeure*)	4	4	1
Delays due to Contracting/Contract Negotiation/Award delays	29	27	1
Actuals (updating previously reported dates to actual occurrence)	172	13	-39

These delay factors suggest program managers (PMs) should plan for the time necessary to deal with oversight, information reporting and both the time takes, as well as the impacts of decisions—internal and external to the program. As the GAO pointed out in a 2015 study, the program office overheads associated with administrative activities added, on average, two years to complete:

> Programs we surveyed spent on average over 2 years completing the steps necessary to document up to 49 information requirements for their most recent acquisition milestone. This includes the time for the program office to develop the documentation and for various stakeholders to review and approve the documentation.

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[2] The data described are from an unpublished study by the author of the delay factors for DoD program 1997–2017. The study is an initial attempt at quantifying schedule delays in program execution with the intent of using those delays to better inform project planning.

Figure 2 provides a trend line and forecast of the delays identified. Using this data, the forecast total delay hours across all programs in 2019 would be 712 hours, and in 2020 that forecast would increase to 729 hours.

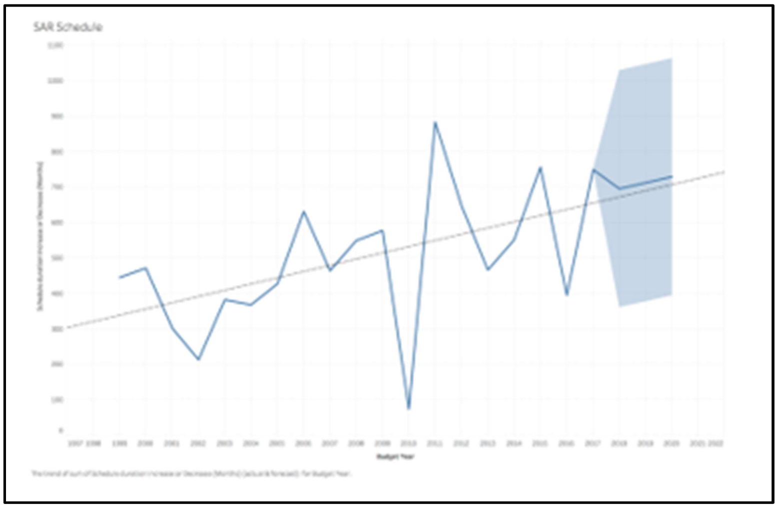

Figure 2. Trend Line Showing Forecasted Schedule Increases

Applying the Data

Our previous paper introduced the rework concept, shown in Figure 3. As noted, the CPM/PERT approach to scheduling precludes the use of data at the program schedule level. And, while some companies track task estimation data, that data is often proprietary and more focused on technical process estimation (Godlewski, Lee, & Cooper, 2012).

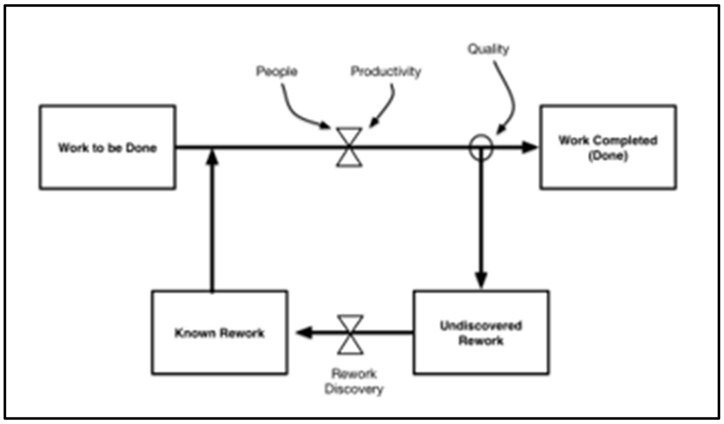

Figure 3. The Rework Cycle

The basic assumption that work proceeds as planned in the network from start to finish is naïve at best (Franck et al., 2017). System dynamics can account for the feedback that results from decisions made in the execution of a project. A project network using CPM/PERT techniques depends on each task being completed in the defined order established. While most PMs attempt to maintain that order, the reality of dynamics intervenes. That reality means that network analysis cannot capture the progress of a project (Williams et al., 1994).

A tool used in system dynamics to capture cause and effect is a causal map. The causal map becomes a tool used for the development of a model of the delay factors identified. Figure 4 is an initial causal map capturing some of the identified factors in weapons system program schedule delays. The factors shown are a subset of those identified for brevity in this paper.

Delay factors plus the effects of rework, decision wait time, tasks start delay, and other disruptions result in the PM (or PMO) recognizing a schedule problem (delay in the critical path). Invariably, the PM must take action to attempt to return the project to the equilibrium expressed as being on schedule. Thus, the PM could approve overtime, reschedule, or take some other mitigation. The pressure to get back on schedule is driven by many factors including cost considerations, pressure from the oversight organizations, and in weapons systems development, the necessity of delivering capability to the warfighter in the most efficient time. Regardless the reason, the PM “does something.” The plus and minus signs indicate the effect of the actions taken.

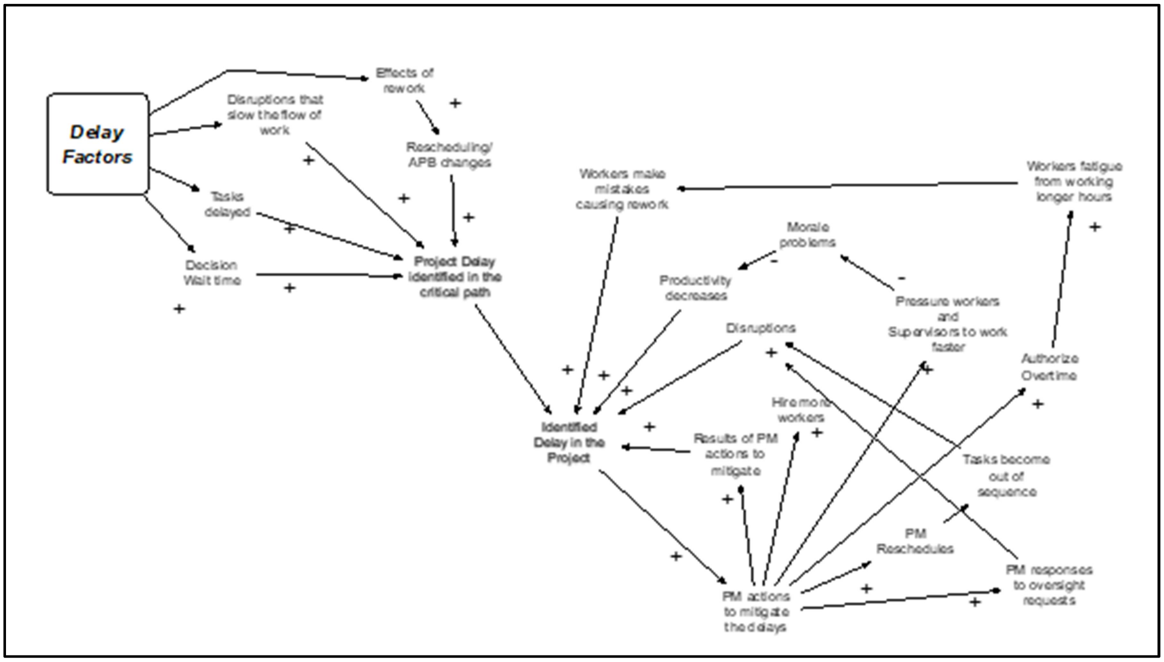

Figure 4. Delay Factors Triggers for Project Delays
(Howick, 2003)

A project is a dynamic system with feedback loops and, invariably, decisions taken to address one problem have an impact on, or create new problems. For example, approving overtime does initially address schedule issues as more work is being done in shorter periods. However, a recognized problem of overtime is fatigue. Fatigue causes workers to make mistakes, and those mistakes result in having to redo the work, thus perpetuating problems that were thought solved.

Similarly, hiring more workers causes more problems. Assuming the new workers have the requisite skills, they need to be trained/acclimated to the actual project situation. In the *Mythical Man Month*, Brooks (1995) explained how this concept works in software development. In reality, it is universal.

Finally, while many of the delay factors identified from the SAR analysis can be explained in Figure 4, others require further examination. One of the biggest challenges is the area of decisions, both internal and external. The internal decisions drive many of the actors discussed above. However, the PM must also deal with external decisions that can eventually impact the development.

Figure 5 is a notional graphic that represents a generic decision cycle in the context of the rework cycle. While the results of this data analysis included rework, the majority of the identified delay factors were decision focused. Those decision centric factors included represent this decision cycle. The notation is shown between the work to be done and work completed boxes because many of the decisions identified occur outside the project manager's purview. The exogenous factors identified cause either reactions to those factors, or force other internal decisions. While not normally a part of the rework cycle, we suggest that a formal appreciation of a decision cycle, and the time it takes for decisions to be made both internal as well as external to the program management cycle, must be considered.

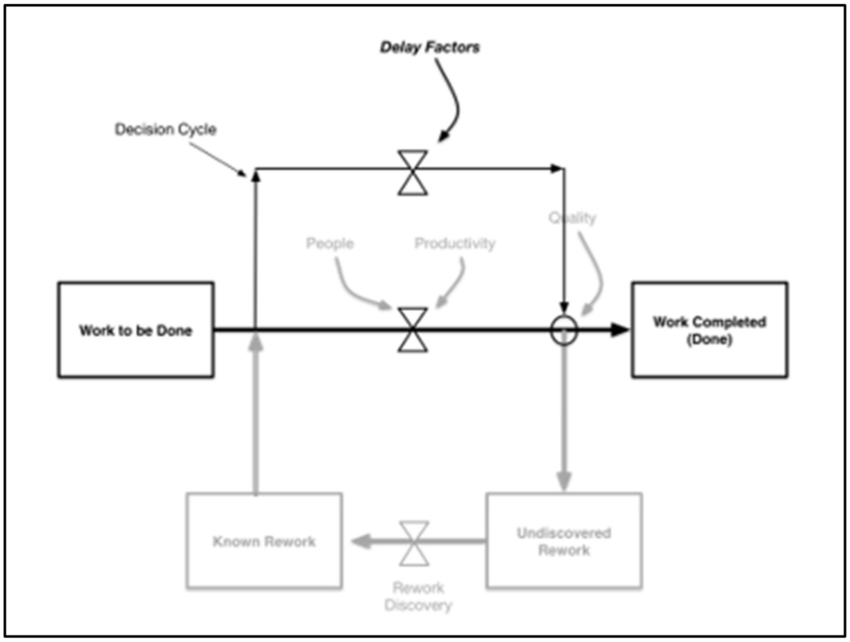

Figure 5. Notional Decision Cycle Added to Rework Cycle Diagram

Conclusion

This section continued the discussion on using system dynamics to better understand, plan, and execute defense acquisition programs. This section presented schedule information gleaned from Selected Acquisition Reports, and suggested a model to show how that information can be best understood in the context of the decisions necessary to model weapons system acquisition programs. To be clear, we are not advocating to replace the CPM/PERT methods used today. At best, system dynamics is an adjunct to those methods in use. Instead, we suggest that we should recognize the dynamics at play in any weapons system development, and once recognized, use the appropriate tools to better our execution.

No program manager sets out to overrun a schedule; "However, clients increasingly value not only cost and schedule control but cost and schedule certainty" (Godlewski et al., 2012, p. 18). Those clients for defense acquisition products seek certainty as well, both in cost and schedule. It is no secret that current methods for estimating and executing schedule are insufficient. In fact, certainty is one of the potential benefits of this examination of schedule factors. Project certainty starts in effective schedule planning by using the right tools.

F-35 Case Study[3]

Much has been written about the F-35 program, in many venues. Defense acquisition professionals know a lot about “what” has happened. “How” and “why” it has happened is less clear. Our last essay (Franck, Hildebrandt, Pickar & Udis, 2017) undertook an inquiry as to the “hows” and “whys” of this case. We asked how a program that traces its lineage to the Common Affordable Lightweight Fighter became the F-35—which is not very common (Bogdan, 2012), definitely not lightweight, of debatable affordability (see GAO, 2017; Capaccio, 2018), and arguably not a fighter (Airpower Australia, 2017).

The publicly-available literature was not terribly enlightening, although a few interesting clues were discernible. We closed with an intent “to learn more in future inquiries” (Franck et al., 2017, p. 420). Since then, the field interview method has brought new insights to many aspects of the F-35 program.

Given space limitations, we concentrate on some useful hypotheses we’ve gleaned—the assessment of which is for further inquiry. These hypotheses[4] concern program management, technology and engineering, and the lure of new technologies. Careful readers will note that they are not mutually exclusive and are interrelated in a number of ways.

Program Management

The management narrative can be organized as poor program structure from the start: an underequipped and over-burdened program office—all of which enabled bad decisions.

Program Structure

The program turned out to be well-designed to fail. Basically, Lockheed-Martin (LM, the prime contractor) had considerable discretion and control over a highly complex program with a vague set of requirements. Moreover, the incentive structure was not well designed (“poor” according to at least one authority). This produced a Principal-Agent problem (e.g., Kreps, 1990, Chapter 16) with the Principal (DoD) unable to fully monitor the agent’s (LM’s) behavior, or to incentivize good behavior. One result was a strained relationship between LM and DoD (“worst I’ve ever seen”; Bogdan, 2012).

The program strategy reflected a number of optimistic framing assumptions. These included joint programs saving money, plus new, but untried, methods expected to significantly reduce risk and time. This latter set included the assumed benefits of recent acquisition reforms and better simulation methods expected to reduce flight testing. All this led to an aggressive schedule—involving tight timelines with a high degree of concurrency accepted *a priori* (Blickstein et al., 2011, p. 37).

When these assumptions were not borne out, schedules stretched out and costs grew. The RAND Root Cause Analysis, for example, concluded “optimistic cost and schedule estimates” constituted a major cause of program difficulties (Blickstein et al., 2011, p. 37).

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[3] We are greatly indebted to a highly-placed, well-informed DoD official for many of the insights that underpin this section of our paper. Chatham House Rule applies.

[4] Although readers will likely not agree with all the details, few, if any, will be surprised.

Program Office

The F-35's DoD management team was assigned a task that included serious complexities in both technical and management dimensions. Moreover, the management difficulties included coordination of 11 stakeholders (three U.S. and eight international) with varied operational needs while complying with the U.S. ITAR (International Trade in Arms) regime.

Additionally, cascading effects of program difficulties made the work even more complex. One example was weight growth early in the program (precipitated in part by entering development with a slender weight growth margin), which necessitated a larger engine, which in turn necessitated a major redesign of the fuselage to accommodate the larger engine (Blickstein et al., 2011, p. 53)—with one major result being cost growth and schedule delay. The acquisition strategy turned out to be something of a "house of cards."

Given its highly complex and demanding mission, the F-35 Program Office was woefully underequipped at crucial junctures. Requirements discipline in the formative period has been characterized as "weak" and unable to deal effectively with a number of changes internal to the program (e.g., tech insertions, revised development plans) and external (e.g., threat evolution). In addition, there were, at times, mismatches between Program Office needs and personnel skills aboard.

Some tools of program management were inadequate—particularly for schedules. From a program management perspective, schedule management tools proved hard to use, not well tied to resource use, insufficiently flexible to account for risk and program perturbations, and not supported with data from historical experience. As program difficulties arose, there was no credible means available to estimate schedule implications.

These are, of course, difficulties that afflict any defense acquisition program. However, new, complex, difficult, advanced systems like the F-35 suffer more. Another difficulty was rotating new program executive officers (PEOs) every few years. Accordingly, both the opportunity and incentive to reorient the program were in very short supply. This particular pattern was broken in 2012 with an indefinite-term PEO.

In addition, as problems continued, the Program Office was subject to a rather onerous oversight regime, with attendant political pressures and constraints. The one-year F-35B probation period is one example (Franck et al., 2012, esp. pp. 57–59).

Program Execution: Bad Decisions

The factors cited above facilitated bad decisions. The flawed assumptions that underpinned the acquisition strategy did not receive sufficient scrutiny (perhaps related to leadership tenure). In an atmosphere of pervasive optimism, relatively pessimistic assessments (such as the CAIG report in 2001) had little apparent effect on program management (Blickstein et al., 2011, p. 37). Requirements remained in some degree of flux well into the program life, with corresponding effects on program stability.

Heavy reliance on test data (e.g., reliance on simulations and test data from non-scale airframes) greatly delayed the test program when those presumptions proved inaccurate.

The F-35 Helmet Mounted Display (HMD) was a major technical advance—with great promise but high risk and no guarantee of success. However, a natural programmatic hedge, head-up display (HUD), was cancelled early in the program. This meant that lags in HMD development became a major threat to program success (Bogdan, 2012).

Program Office personnel clung closely to a commonality standard among the three models, with cost growth and delays associated with fixing one model's problems among all three models. (This seems to make sense if the F-35 is one unified program; less so, if there are three programs with commonalities.[5])

Technology and Engineering

The optimism that set the theme for the management strategy also pervaded the technology assumptions. There was a strong proclivity to underestimate the difficulties and risks. While, for example, there was a fair amount of experience with stealthy aircraft designs within the U.S. defense industrial base, the F-35 was nonetheless a major leap forward. As RAND's Root Cause Analysis noted, the basic technical requirements were very demanding. This is illustrated in Table 2. Given the high degree of commonality specified for the F-35, if one model needed to meet the design objectives in the table, all models need to achieve those objectives. It took considerable ingenuity to design an airplane whose morphology accommodated all these requirements (Blickstein et al., 2011, esp. p. 37).

Table 2. Required Features for F-35 Design

(Adapted from Blickstein et al., 2011, Table 4.6, p. 49)

	STEALTH	STOVL	SUPERSONIC
Engine Inlets	Small	Large	Specific shapes
Fuel Capacity	Internal only	Small	Large
Airframe Shape	Specific (radar signature)	Specific (weight distribution)	Specific (speed regime transitions)
Materials	Stealthy airframe skin	Light skin for vertical landing	Strong skin (speed regime transitions)

Accordingly, there was little margin for error or unexpected difficulties; one example was the 6% allowance for increased weight. That reserve was exceeded early in the program, which necessitated a major redesign exercise (Blickstein et al., 2011, pp. 47, 53).

Given the demanding nature of the original design and slender margins for error, there was nonetheless a definite willingness to push the technical envelope. Thus, for example, the Helmet Mounted Display (discussed above) was a major technical advance—with a natural hedge (HUD) discarded early.[6]

There was likewise a propensity to trust new and promising, but not fully validated, engineering methods. These included computer simulations substituting much of the testing normally accomplished in the air. The result was a test program generally behind and in a catch-up mode (e.g., see DOTE, 2016, esp. p. 31).

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[5] LtGen. Bogdan (2012) eloquently stated the separate-programs perspective.

[6] Reasonable people can disagree as to whether this is a management issue, technical issue, or both.

The Attraction of New Technologies

Technology insertions occurred with some frequency during the F-35 development program. These included the Autonomic Logistics Information System (ALIS) and the Helmet-Mounted Display. ALIS seems to have been regarded as merely the logical extension of onboard aircraft diagnostics (Steidle, 1997, p. 9). However, more than a decade later, problems with ALIS were (rightly) viewed as an existential threat to the entire program (Bogdan, 2012).

Likewise, the evolution of the F-35 from an affordable, limited-capability companion for the F-22 (*inter alia*) to a "situational awareness machine" seems to be related to some major advances in sensor capabilities that the F-35 program adopted. (It's also true that the stakeholders were involved: "JAST … was … designed to have the smallest possible sensor suite and be dependent on external information sources … [But] most of the export countries did not have (those sources) in their inventory" and the F-35 became a battlefield information producer [Keijsper, 2007, p. 135]).

Such initiatives, taken in isolation, were undoubtedly viewed as sensible at the time. However, the cumulative effect of a series of sensible decisions can be a horrible end result.

The last word on the new technologies and platform performance issues might well come from General Deptula (2016):

> Current systems are largely expected to operate in a semi-autonomous fashion, with a basic level of collaborative engagement with other platforms. These shortcomings place pressure on individual assets to possess numerous internal capabilities. The complexity inherent to this approach drives lengthy development cycles, which in turn leads to requirement creep, time and cost overruns, and delays in capability. (pp. 6–7; emphasis added)

This looks like an indirect reference to the F-35 we're getting.

Some Questions for Further Investigation

1. Can an acquisition program schedule become self-stretching? A simplified version of this hypothesis goes something like this. System complexity entails a lengthy development program. Over time, various technical improvements present themselves—some of which are adopted. These technical insertions (even if done well) nonetheless add to system complexity or estimated program schedule (or both). This cycle is summarized in Figure 6.

While this influence diagram seems plausible, the strength of these connections and their total effects on program schedules are subjects for further inquiries.

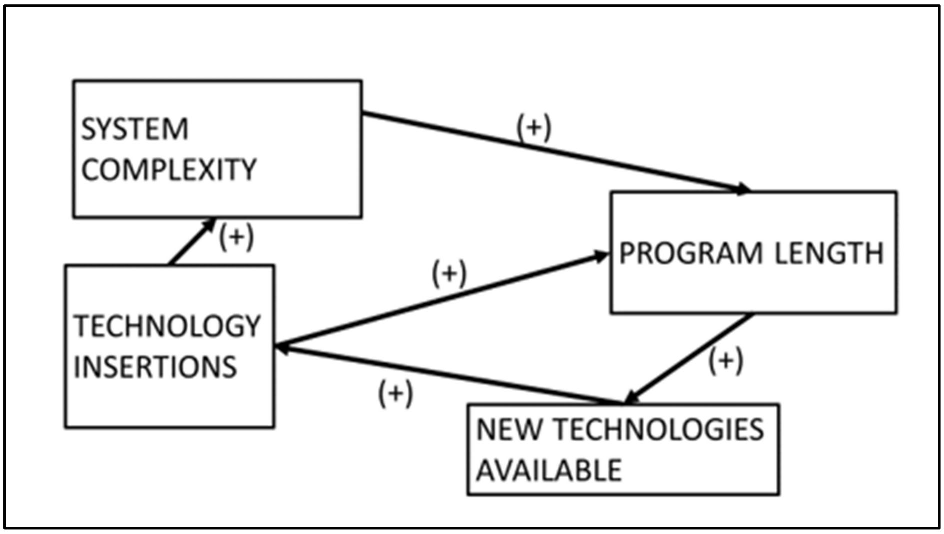

Figure 6. Self-Stretching Acquisition Program Schedules?

2. To what extent do weak schedule estimation and management tools affect program performance? There are excellent reasons to believe that scheduling estimates are sometimes not realistic. What schedule management tools do program managers and program offices lack? How can those gaps be addressed?

JCIDS Manual (CJCS, 2015, p. A-9) recommends tradeoffs among system cost, performance, and schedule. Program managers have reasonably good cost estimation tools, reasonably good indicators of system performance, but not good ways to estimate schedules—especially if the original program experiences requirements growth.

This question offers some scope for gap analysis—to be investigated through case studies and interviews with subject matter experts.

Measuring System Performance[7]

Updating combat system performance measures is important for at least two reasons. First, a better understanding of combat capability in the information age could significantly improve defense policy and planning. Second, a credible (preferably scalar) measure of combat capability could contribute much to schedule estimation—through better schedule-estimating relationships.

We've chosen to start with air-air combat systems. In a previous paper (Franck et al., 2017, esp. pp. 423–425), we explored a Lanchester aimed-fire model with various complications: stealth and command control, in addition to lethality and relative numbers. Results were interesting, but just a start.

Air combat in the near future will involve weapons committed from various types of platforms. Accordingly, we extend our previous model to include engagements "called in"

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[7] This particular discussion has been abridged to fit the Proceedings' space limits. A more detailed version is available on request at cfranck215@aol.com.

from other platforms. One variant along this line is using non-stealthy aircraft (such as F-15s and B-52s) as weapons carriers whose targets are identified and assigned by fifth-generation aircraft—such as the F-35.

Accordingly, some aircraft ("scouts," S) will use their situational awareness capabilities to acquire hostile assets and then assign other aircraft ("weapons carriers," W) to engage them.[8] This assignment entails a useful networking capability. In this concept of operations, the shooter aircraft are primarily weapons carriers—and consumers of offboard sensors.

A Lanchester-Type Variant for Contemporary Air Combat[9]

Consider a stylized air battle scenario about one decade in the future:

> During the opening days, fighting focuses on the battle for air superiority as aircraft from both sides clash over contested territory. As the conflict continues, fifth-generation aircraft seek out, degrade, and destroy advanced SAMs in contested territory, creating a more moderate threat environment. This enables legacy aircraft to operate alongside their fifth-generation counterparts. (Harrigian & Marosko, 2016, pp. 7–8)

This suggests two major changes expected in the foreseeable future. The first is heterogeneous air combat forces: consisting of stealthy aircraft, plus a force of "legacy" combatants. The initially contested airspace contains stealthy fighters, with any older aircraft being quickly eliminated in that area (Barrett & Carpenter, 2017, esp. p. 5). However, those non-stealthy platforms can actively participate as weapons launchers whose fires are assigned by the fifth-generation aircraft acting as scouts—or other assets with command control capabilities.

Second, air combat will no longer be merely platform-on-platform engagements, but rather network-on-network, information-centered combat. One manifestation of this line of reasoning is the "kill web" concept, which features highly-networked forces with decentralized lethality and sensor capabilities, but most importantly decentralized decision making. Kill-web units take independent action, and are not "micro-managed" (Timperlake, 2017).

A related idea is the "combat cloud": "a model where information, data management, connectivity, and command and control (C2) are core mission priorities. The combat cloud treats every platform as a sensor, as well as an 'effector'" (Deptula, 2016, p. 1). In particular, operational decision making is spread throughout the network, with the "entire area of responsibility … functioning as a CAOC [Combined Air Operation Center]" (Deptula, 2016, p. 7).

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[8] Given the F-35's limited internal weapons carriage, the role of finding hostiles and assigning others to engage is likely the primary role. We (Franck & Udis, 2016) have suggested "joint *scout* fighter" as a more descriptive name than "joint strike fighter."

[9] Taylor, Vol. II (1983, Section 6.13, pp. 318 ff.) provides a rigorous exposition of a starting point for our model.

The Data-To-Decision Problem

Kill webs and combat clouds are very promising. However, proficiency in network-based combat is a military advantage only to the extent it leads to better decisions than the enemy's (Gouré, 2018). Moreover, decentralized decision making is integral to the kill web and combat cloud concepts of operation. That makes achieving a reasonable degree of unity of effort a significant problem.

A simple example suffices to illustrate the point. Suppose there are two targets (A, B) of equal value, with associated (decentralized) decision makers (DA, DB). Suppose also there are two remotely-located weapons available for assignment (a, b), and that probability of kill varies with both weapon and target, as shown in Table 3.

Table 3. Simple Weapons Assignment Problem

WEAPONS	TARGETS	
	A	B
a	.9	.8
b	.7	.2

Clearly the optimal assignment is Weapon "a" to Target "B," and Weapon "b" to Target "A"—with 1.5 targets destroyed on average. However, structuring and solving such an assignment problem generally assumes a central authority with information that's both timely and sufficient.

In a *decentralized* decision mode, both Decision-Makers A & B (DA & DB) will note that Weapon "a" is better for his target. But there's only one Weapon "a." If DA happens to call in Weapon "a" first, then DB is stuck with Weapon "b," and targets destroyed declines to 1.1. (If DB calls in Weapon "a" first, then all is well, and 1.5 targets are destroyed on average.)

Timperlake (2017), in fact, proposes that the DA and DB simply ask which weapon is best for their target. That may or may not work out well. One ACC Commander, Gen Hawk Carlisle, posits (take everything from) "subsurface to on orbit," automatically piece it together, and "put it into the warfighter's hands in a way that … now they become the decision-makers" (as cited in Church, 2016).

Two comments: First, both perspectives assume a degree of situational awareness that goes beyond standard definitions such as "knowing real-time the current position, classification, condition and recent history of all items of military interest in both the physical and virtual battlespace" (Franck, 1995). Both Timperlake and Carlisle apparently assume that those decentralized decision makers also know target-weapons matchup characteristics well enough to make good choices among weapons available. This entails, *inter alia*, knowing plans (especially near future) of all relevant, friendly decision makers.

In short, the open literature indicates that translating shared situation awareness through a web of decentralized decision makers to produce a reasonable approximation of unity of effort is not yet completely understood, let alone solved. And the Air Force Air Superiority Flight Plan (U.S. Air Force Enterprise Capability Collaboration Team, 2016) apparently shares this opinion, recommending,

- a "data-to-decision campaign of experiments (to) examine how to fuse data from cloud-based sensor networks into decision quality information" (p. 7),
- "non-tradition concepts" for Battle Management Systems (p. 8), and

- development of new Command Control capabilities to provide “materiel and non-materiel solutions (that) should provide commanders in 2030 with the ability to synchronize forces across domains” (p. 8).

Assessing Air Combat Performance

Effective air combat forces are proficient in accomplishing the following tasks—which are generally accomplished sequentially, with accomplishment of all of them needed to ensure success:

- Cueing friendly forces of enemy activity (or early warning)—accomplished by assets with intelligence and reconnaissance capabilities
- Detecting, identifying, and tracking enemy forces—accomplished by surveillance systems
- Assigning forces to targets—command and control (C2) assets
- Engagement of targets—combat platforms and associated weapons
- Assessment of engagement results—surveillance systems

Timperlake (2017) essays a framework for contemporary combat capability called “payload utility.” This is the ability to acquire, engage, and destroy targets. What’s important for assessing near-future air combat is that the associated tasks are assigned to an entire network, with individual units calling on offboard resources within the network. For example, a target can be cued and detected by an early-warning sensor suite; identified and tracked by surveillance assets; be assigned to friendly forces by C2 assets; localized by a combat system—which engages the target through a weapon fired by yet another system; and then followed by an assessment of engagement results.

Simple models suggest that force sizes, weapons, stealth, and coordination are key variables in a credible measure of air combat capability. One look appears in Figure 7.

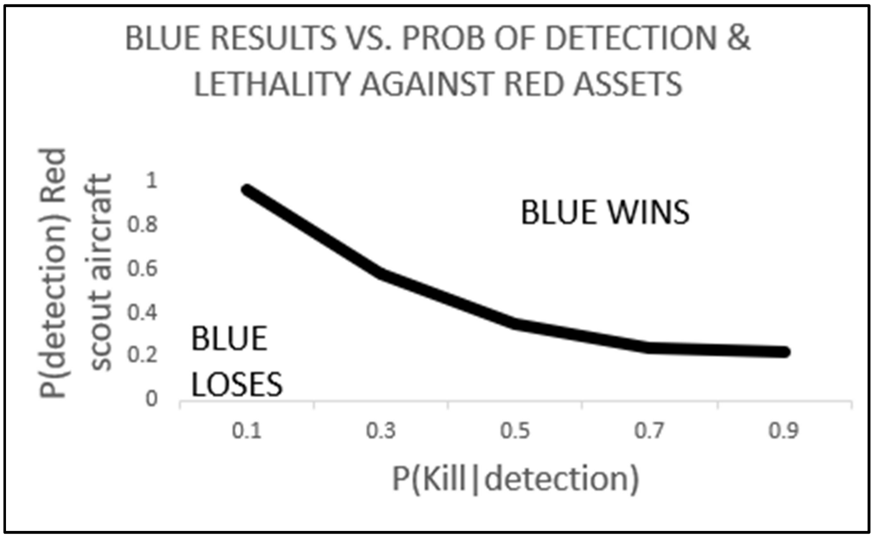

Figure 7. Combat Results VS. Detection and Lethality

The figure highlights important aspects of combat capability. First is the importance of “matchups” such as ISR versus stealth, and weapons versus targets’ countermeasures. Second is that (from a Blue perspective) it’s important to find Red targets (defeat Red stealth) and to have weapons that can defeat Red self-protection countermeasures. These aren’t terribly profound insights. However, they suggest we might be better off with fifth-gen weapons on fifth-gen airplanes than with fourth-gen weapons on sixth-gen airplanes. Finally, substitutions are indeed possible. For example, shortfalls in detection and tracking can be overcome with better weapons.

Next Steps

First, improve the model above to better account for the problem of coordinating a decentralized decision-making process. Among other things, we're hoping that the recommended Air Force studies and experiments along this line will include some unclassified results.

Second, try a more fine-grained approach to modeling future air combat. Agent-based simulation might be a useful method. This would, of course, be a major effort but with potentially major insights.

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