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Telling Time: Getting Relevant Data for Acquisition Schedule Estimating Relationships

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Abstract

This paper is part of a research agenda outlined in Franck et al. (2016) directed toward improving the realism of defense acquisition schedules. Defense acquisition schedules have long been a difficult problem. In this particular effort, we consider primarily the case of the 737MAX, which has been a fortuitous example of the risks of scheduling-by-fiat. We analyze the 737MAX misadventure using systems dynamics and root cause analysis methods.

A fundamental question for defense acquisition schedule estimating is the extent to which schedule drivers vary (or don't) across various defense acquisition programs. If the programs are, in fact, idiosyncratic in nature, then we have prospects of explaining observed schedules (with program-specific explanatory variables). However, to the extent that common themes drive schedules across whole classes of programs, we have better prospects of predicting expected schedule length. This paper aims to (a) present a useful perspective of this question and (b) offer suggestions for the way forward.

Keywords: Acquisition Schedules, Data Science

Why Estimating Acquisition Schedules Is Difficult

Schedule is the least understood of the three critical outcomes in weapons system development (cost, schedule, and performance) by both researchers and practitioners. As much art as science, scheduling is an aspect of the decision-making necessary to develop and deliver combat capability. The science is driven by the necessity to accurately capture the elements of the schedule to provide an accurate starting as well as measurement to the program.

Acquisition schedules have long been identified as a troublesome issue (e.g., Peck & Scherer, 1962, ch. 16). And the art of estimating schedules (or explaining schedules) has received decades of attention since. One approach to this problem has been schedule estimating relationships (SERs), which posit an orderly relationship between actual schedule and observable (hopefully quantifiable) factors relevant to any given program (Franck et al., 2016, pp. 99–100). Franck and colleagues also offered a preliminary list of explanatory variables for an SER.

Schedule estimates (ex-ante) and schedule analysis (ex-post) are easier said than done. They involve both art and science. The "science" part includes a systematic study of the relevant data, often distilled into quantitative relationships. The "art" aspect arises, inter alia, from the inherent complications in any endeavor with a schedule. And the discussion that follows provides insights into complications attendant to any schedule estimation.

As Pickar and Franck (2019) pointed out, there are hazards to schedule estimates without a reasonable grounding in past experience. We think a promising approach toward that end is SERs, well informed by experience. If properly developed and applied, this tool can significantly improve life for acquisition professionals.

It might also improve the lot of those who study acquisition matters. For example, Trudelle et al. (2017) studied how likely defense acquisition programs were to stay within cost and schedule bounds. A vexing issue in this effort was the dubious reasonableness of the original schedule estimates from which they measured overruns. Discussing the issue of major defense acquisition programs having a greater likelihood of leaving estimated bounds, they encountered the issue of whether the initial schedule (and cost) estimates were a matter of reasonably confident expectation: Addressing the common practice of "optimistic" initial estimates, the authors note, "We have seen too many . . . schedule times (that) are simply unrealistic" (p. 611).

Some Near-Universal Schedule Estimating Complications

The "Incidentals": A Road Trip Schedule Estimating Problem

"People always fail to plan for the incidentals."

Time to complete (schedule) can be affected by factors external to the program. Consider a simple example. Suppose a firm (A) specializes in hauling small, high-value cargoes over relatively long distances by road. Suppose also "A" is bidding for a contract to pick up cargo at San Antonio International Airport and deliver it to Chicago O'Hare on a date six months in the future, with time en route a significant factor in the contract award. A confirmed optimist would note that the great circle distance between those points is 1,040 (statute) miles—which (if practical) implies about 15 hours of driving time (averaging 70 mph). And a confirmed optimist might well propose that as an estimate. A more realistic estimate is to pick the fastest route with actual roads—which turns out to be almost entirely interstate highways. This works out to 1,250 miles—about 18 hours. (See Figure 1.)

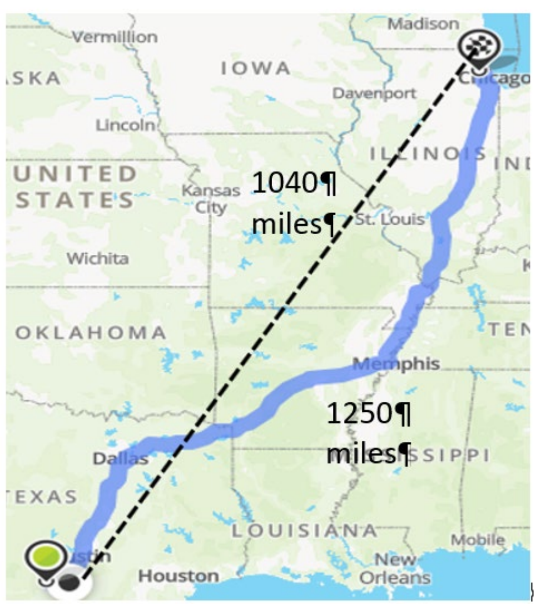

Figure 1. Road Trip Schedule

The second estimate is more credible, but there's a tendency to underestimate the role of incidentals. These include stops for gas and other things, plus delays due to rush-hour traffic. Planning factors for this set of variables are relatively easy to formulate. However, the possibilities of mechanical breakdown or mishap are more difficult.

Also, there are external factors that may arise. A delay in package arrival in San Antonio could change the rush-hour delays. Road construction would also be a factor (and probably not easily predicted six months ahead). One way to improve the estimate might be reliance on data from previous trips of this nature.

As Riposo et al. (2014, p. 41) point out, schedule drivers include factors outside the program itself. These include funding stability (or not). Other external factors include the following:

- acquisition policy regime (McNicol & Wu, 2014),
- funding "climate" (McNicol, 2015, 2020),
- external shocks, such as significant funding changes, new requirements (GAO, 2010), bid protests with associated litigation (Amara & Franck, 2021), and
- "acts of God" (such as hurricanes; Werner, 2019).

Managed Processes and Outside Observers

Processes whose outcomes are influenced by management actions are more complicated than those determined by nature or a simple optimization process.[1] Such complications can arise when program management must make trade-offs among multiple outcomes, such as cost, performance, and schedule.[2]

Large projects entail significant management effort—to avoid inefficiencies and make appropriate balancing of multiple goals. However, even straightforward projects lead to trade-offs and complications—particularly for prognosticators.

Consider a very simple project consisting of two tasks, M and N. This is summarized in Figure 2. The project tasks are accomplished sequentially by two teams (Teams M and N, respectively).

Model variables determined by nature are the following:

- Time to complete Task M (TCM) is 1 and time to complete Task N (TCN) is 2, each with probability 0.5, determined independently (known unknowns).
- TCM (TCN) is assumed known for one period after Task M (Task N) is started.

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[1] Such as maximizing output quantity, subject to input constraints.
[2] And as the *Manual for the Operation of the Joint Capabilities Integration and Development System* (CJCS, 2018) and related directives make plain, program managers are expected to do just that.

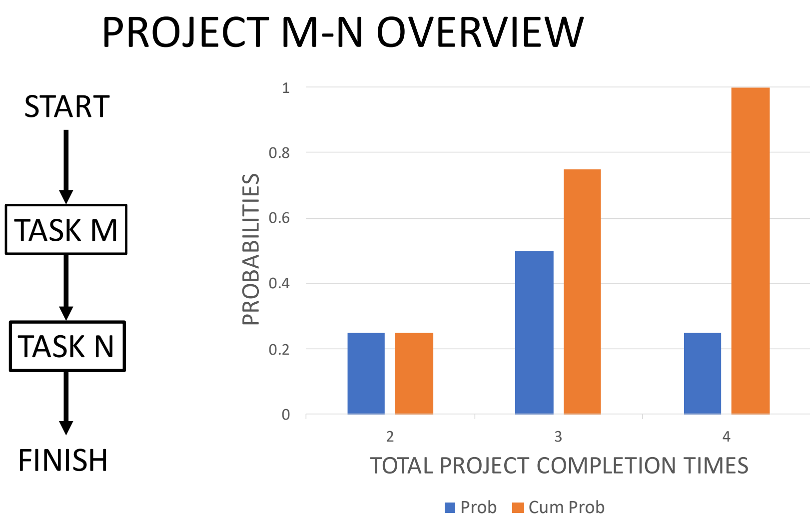

Figure 2. Project M–N

Note: Probabilities of project completion times assume no delays. (Incurring risk of delay is a management decision.)

The manager's decision variables are the following:

- TPN: when Team N is assembled and ready for Task N (TPN = 1 or 2);
- TM (TN): time spent with Task M (N) = 1 or 2.

Outcomes depend on task completion times (TCM, TCN), times spent on each task (TM, TN) and TPN, with

- Schedule = TM + TN + Delay[3]
- Cost = TM + TN + Wait[4]
- Wait = 1, if TM = 2 and TPN = 1.
- Delay = 1, if TM = 1 and TPN = 2.
- Performance ≈ [(TM/TCM)^0.5 + (TN/TCN)^0.5] * 50.[5]

Management has three decision variables: TM, TN, and TPN. Setting TPN = 1 assumes a risk of cost increase if TM = 2, causing Team N to spend one period idle (but paid). If TM < TCM or TN < TCN, then the management sacrifices performance in favor of schedule and cost.

[3] Schedule can vary between 2 (TM = TN = TPN = 1) and 4 (TM = TN = 2). If TPN = 2, and TCM = 1, then one period passes with no work done, a wait which adds one period to completion time (scheduled).
[4] Cost can vary between 2 (TCM = TCN = 1) and 5 (TM = TN = 2; and TPN = 1). If TM = 2 and TPN = 1, then Team N is waiting for Task M to complete. This adds one unit of cost.
[5] Performance of the developed product depends on time allocated to each task (M,N) versus time to complete the phase.

Project Management Scenario

As we have already noted, project management is expected to care about performance, cost, and time to complete (schedule). The management time line looks like Table 1.

Table 1. Project Management Decision Sequence When Managing for Performance

Time	Information	Decision Variable(s)	Outcomes Emerging
0	Initial set (above)	TPN	
1	TCM (1 or 2)	TM (1 or 2)	Performance partially defined. Cost, schedule choices narrowed.
TM + Delay + 1	TCN (1 or 2)	TN (1 or 2)	All outcomes determined (performance, schedule, and cost).

Management starts with the information summarized above and must decide at Time 0 when to have the resources for Task N (Team N) in place. If TM = 1 and TPN = 2, then the work stops one period before Task N begins—with attendant schedule implications (delay of one period). If TM = 2 and TPN = 1, then Team N must wait until Task M is complete—with attendant cost implications (Team N in place but idle for one period).

In the rest of this section, we examine the managerial “trade space” if the M–N Project is managed (a) to meet a performance goal, (b) to stay within cost constraints (a budget), or (c) to complete by a specified time (schedule).

In the discussion below, we assume the project is managed for performance, cost, or schedule. That is, performance (cost, schedule) is fixed with cost and schedule (performance and schedule, performance and cost) varied. This leads to an efficient set for the other outcomes. For example, if the project is managed for performance, there is an efficient set of cost–schedule outcome pairs. This can be plotted as a curve, shifting the efficient-set curve as performance requirement changes.

Management for Performance

As noted, the performance achieved can vary from 70 to 100. If TCM = TCN = 2, and TM = TN = 1, then Performance = 70. If TM = TCM and TN = TCN, then performance is 100.

Management strategy depends on the performance goal specified. If Performance must be 100, then, of course, TM = TCM, and TN = TCN. Cost and schedule are then determined if the observer also knows TPN. If project management strongly emphasizes cost (schedule) over schedule (cost), then TPN = 2 (1).

If the performance requirement is less than 100, the program manager (PM) should set TM = 1—with TN = TCN to reach (or exceed) the performance goal even if TCM = 2. Knowing that TM = 1 is a given, then TPN = 1 is preferred since that’s when Task N will start (regardless of TCM). Management can choose TN to reach the goal (and benefits if TCN = 1).[6]

[6] If performance requirement is 70, and either TCM or TCN = 1, then product performance must exceed that requirement.

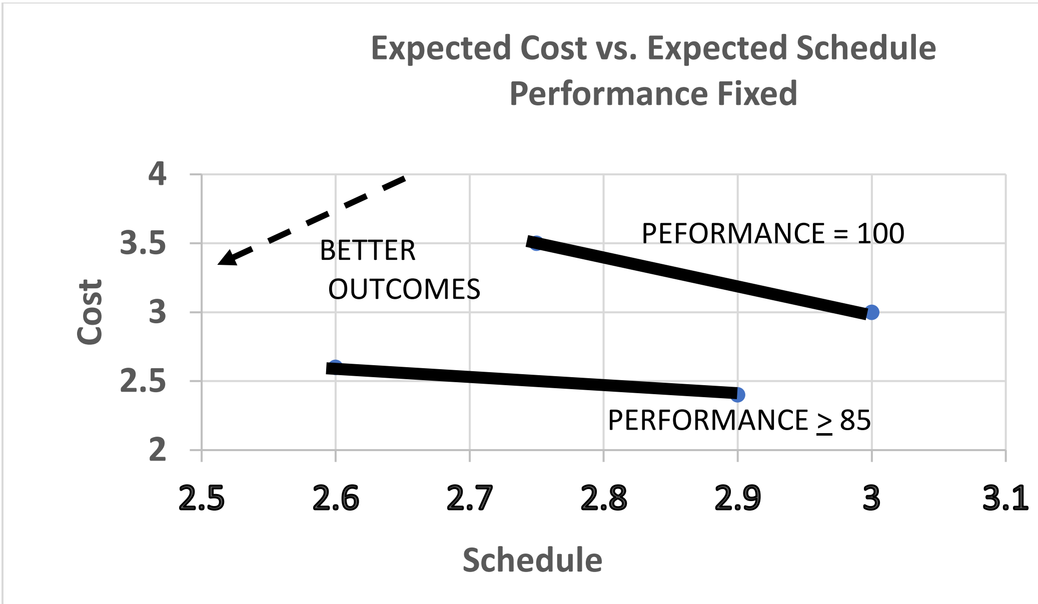

Figure 3. Managing for Performance

Note: Although extending the schedule by one time period automatically increases cost by 1, there's still a cost–schedule trade-off in this example.

Managing For Cost (Fixed Budget)

The trade-off between performance and schedule, with various cost limits, is shown in Figure 3. Clearly, striving for better performance increases both cost and schedule time—or both. Cost can vary from 2 to 5. If TM = TN = 2 and TPN = 1, then Cost = 5. If TM = TN = 1, then Cost = 2.

In this case, since the project budget is fixed, then management must consider trade-offs between performance and schedule. Cost can vary from 2 (TCM = TCN = 1) to 5 (TCM = TCN = 2, and TPN = 1, resulting from Team N waiting one period).

<u>If Cost (Budget) is fixed at 2</u>, then the project must pursue that low-confidence, success-oriented strategy—with TM = TN = 1, with (of course) TPN = 1. If this does pan out, then the project will be highly successful with low cost (2), quick completion (2), and excellent performance (100).[7]

If either (or both) task completion times are 2 (Prob = 0.75), then there is a performance penalty, summarized in Table 2. Since budget dictates schedule, there is no schedule or delay risk accepted in the PM's strategy. (The one path to success entails TPN = 1, with no schedule or cost penalty incurred.)

Table 2. Performance Outcomes With Best Management Strategy and Budget = 2.

TCM	TCN	
	1	2
1	Performance = 100	85
2	85	70

[7] Enthusiasts and optimists tend to tout this as the mostly likely result.

If Cost = 3, then decision space increases with the ability to deal with longer task completion times. An excellent original plan is TM = TCM, with TPN = 2 (to save on expected cost).

If TCM = 1 = TM, then there is a delay (waiting for Team N to get in place). Following that event, there is a performance–schedule trade-off if TCN = 2.

If TCM = 2 = TM, there is likewise a performance–schedule trade-off. At TM = 1, then the TN (decision variable) versus TCN (determined by chance) determines performance, schedule, and cost outcomes. For example, if TCN = 2, then TN = 1 saves time, while TN = 2 increases performance.

If performance is considered much more important than schedule, then expected performance, schedule, and cost are 94, 3.4, and 2.6, respectively. If schedule is considered much more important than performance, then the outcomes are 89, 3, and 2.25.

If Cost = 4, then management decision space increases yet again, with the added option of TN = 2, even if TM = TCM = 2. Once again, TPN = 2 to save money.

The increased budget buys a better trade-off between expected performance and expected schedule. If performance is much more critical that schedule, then expected performance, schedule, and cost are 96, 3.5, and 2.8, respectively. If schedule is more important than performance, then the expected outcomes are 89, 3, and 2.25.

If Budget = 5, then the project is figuratively awash in cash, and management can formulate a can't-miss strategy of TM = TCM, and TN = TCN, with TPN = 1—with the project cost of 2 to 5 (depending on TCN). The schedule–performance trade-off is painless in terms of meeting guidance.

Maximum achievable performance is (of course) 100 with expected completion after three periods. Performance of 85 is possible with TM = 1, TPN = 1, and TN = TCN—with an expected completion time of 2.5. Performance of 70 can be attained with TM = TN = TPN = 1, with the expected schedule of 2. However, performance exceeds 70 with a probability of 0.75 (with an expected performance of 84), even if TM = TN = 1.

The trade-off curve for performance and schedule is shown in Figure 4. Given schedule, a higher budget increases expected performance. Given performance, a higher budget enables a shorter schedule.

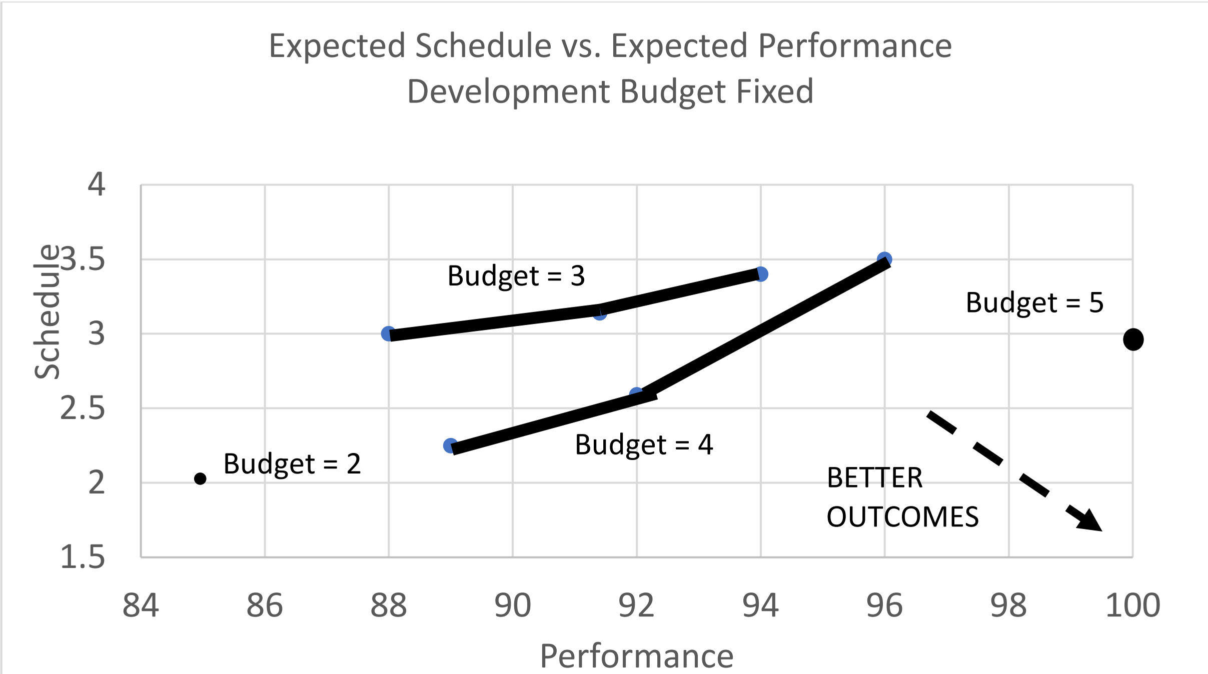

Figure 4. Managing for Development Budget (Cost)

Managing for Schedule

Schedule can vary from 2 to 4. If TCM = TCN = 1 and TPN = 1, then Schedule = 2. If TCM = TCN = 2, TM = TM = 2, then Schedule = 4 (also if TM = 1, TPN = 2, and TN = 2).

If Schedule = 2, there is only one path to success: TCM = TCN = TM = 1 and TPN = 1 (as discussed above for cost restricted to 2).

If Schedule = 3, TPN = 1—to save time at risk of increased cost (due to Team N possibly assembled and waiting).

If Schedule = 4, TM = TCM, TN = TCN, and TPN = 2 (to remove a risk to cost).

Schedule versus performance trade-off curves are shown in Figure 5.

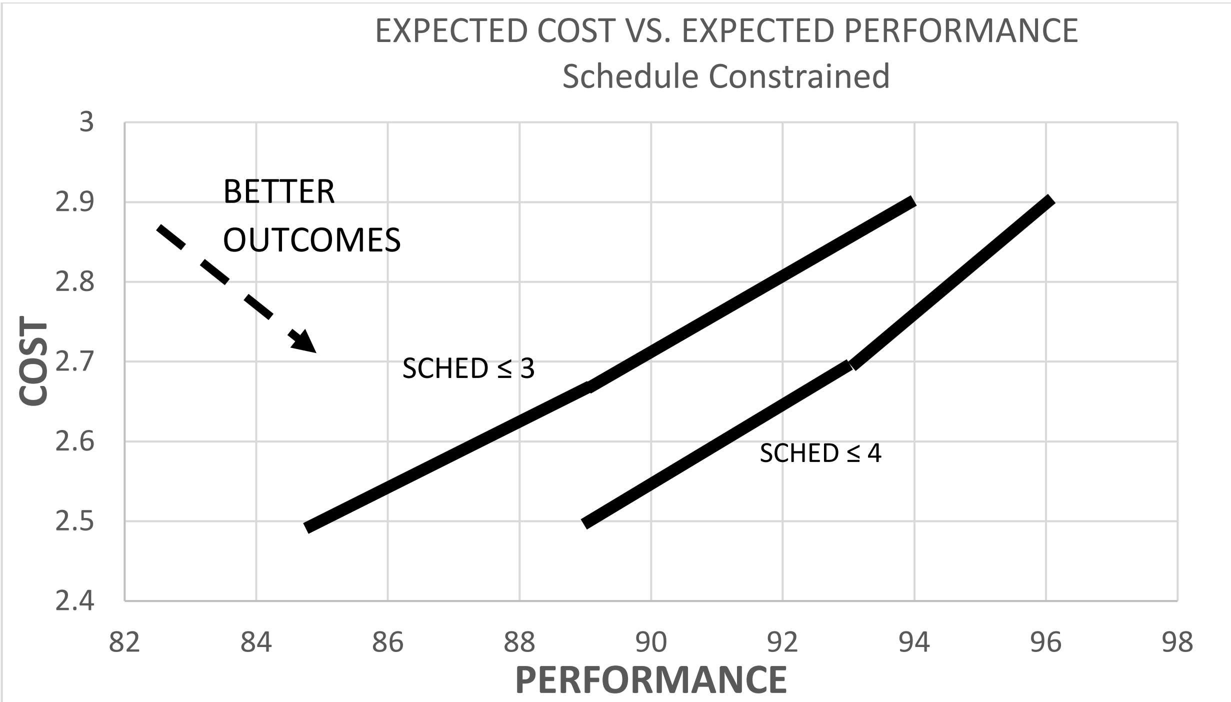

Figure 5. Managing for Schedule

Even a straightforward managed process can pose complications for analysts and forecasters. Any one of the three Joint Capabilities Integration and Development System (JCIDS) macro-outcomes can be changed by management decisions. Thus, estimating schedule means, among other things, predicting PM decisions. Even knowing in advance TCM and TCN is not enough to predict schedule (unless, of course, program management also knows them in advance).

Why this is so: Referring back to Figure 1, suppose performance must be 100. Then management seeking to lessen costs would minimize cost subject to the performance constraint to achieve an expected schedule of 3 and expected cost of 3.

If, however, program management emphasizes schedule, then the expected schedule is minimized subject to the performance constraint (100). In this case, the expected cost is 3.5, and the predicted schedule is 2.75. Note that management decisions determine schedule, as do the unknowns (TCM, TCN). Therefore, an ex ante estimate of program schedule (even with detailed prior knowledge) encounters opaque factors to outside observers using current methods for formulating estimating relationships. In short, actual schedules also depend on decisions the PM makes.

Complications of managed processes appear in the defense acquisition literature. Examples follow.

- The hypothesized relationships can be complicated. For example, Light et al. (2017) included “planned concurrency” in one of their regression models. The resulting coefficient was significant and strongly against expectations (p. 26). The authors offered the highly plausible hypothesis that programs with *planned* concurrency had traits such as (relative) simplicity and were inherently robust with respect to program miscalculations (such as not much associated rework; Light et al., 2017, p. 9).

- A Government Accountability Office report in 2010 cited stable funding as a significant feature of stable acquisition programs (p. 27). The likely Department of Defense (DoD) interpretation would emphasize funding perturbations (including continuing resolutions), impeding effective program execution (e.g., Shackelford, 2021). An Armed Services Committee response (e.g., Adam Smith comment in O'Hanlon, 2021) is likely that program instability causes funding instability. This seems complicated to sort out, particularly in updating schedule estimates. This also indicates that multiple agencies involved in managing a program can indeed add additional complications.
- The literature sampled includes a fair amount of attention to development activities that occur before Milestone (MS) B is offered as an explanatory variable for cycle time from MS B to later events such as low rate initial production (LRIP) or initial operational capability (IOC; Boyd & Mundt, 1995; Harmon et al., 1989). One (perhaps naïve) view is that doing more before MS B means doing less after MS B—with time from MS B to, say, MS C obviously shortened. Another view is that activities before MS B enable a more informed source selection and associated contract—which will likely shorten the time to LRIP in any case. Perhaps both assessments are valid.

What Motivates Those Doing the Schedule Estimates?

Realistic schedule estimates just don't happen spontaneously. Examples from the literature follow.

First, Light et al. (2017), among others, focused on differences (in cost and schedule) concerning the original estimates. However, the authors also noted that those original estimates are flawed in interrelated ways. In the enthusiasm that attends the launch of a new program, there is a "tendency to believe that a current project will go as well as planned "despite previous experience in similar circumstances" (Light et al., 2017, p. 2). This has been dubbed the "planning fallacy" (Kahneman, 2011, pp. 249–251; O'Neil, 2011, p. 286).

Second, source selections have incentive structures that discourage conservative (and more realistic) estimates by prospective vendors—since realistic estimates result in being less likely to get a high-stakes contract. As one participant put it in the context of the advanced medium-range air-to-air missile (AMRAAM) source selection, "There is only one program like this every 30 years, and programs last about that long, so you're driven to go after this work. . . . Sometimes it's a matter of staying in the business" (Mayer, 1993, p. 10).

Third, while there are potentially serious risks associated with winning the contract and being unable to deliver as promised, these are encountered after the "fundamental transformation" of competitive selection to something like a bilateral monopoly (one buyer and one seller) in which even a firm in serious execution difficulties has substantial bargaining leverage (Williamson, 1996, pp. 13, 60–61). It's generally better to have the contract (even with difficulties) than being on the outside and looking in.[8]

In short, those who know most about the proposal in question are generally (a) highly optimistic and (b) incentivized to be optimistic.[9] This strongly discourages realistic schedule estimates at the program start.

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[8] The current state of the KC-X aerial tanker program is illustrative. Boeing's KC-46 won the contract, but the KC-46 still has serious operational shortfalls a decade later. Nonetheless, recent Airbus Group offers to supply their KC-45s have not gone far, at least not yet.

[9] This set of incentives arises in part from the DoD's tendency toward long-term, high-value, winner-takes-all source selections.

Acquisition Programs: Commonalities Versus Differences

This is a significant issue in the study of defense acquisition schedules. As noted above, if acquisition programs are inherently sui generis, then the critical schedule drivers may not emerge until the program is well underway—which leaves (ex ante) schedule estimators a challenging task. Their lot improves if there are indeed common factors.

Our discussion begins with two studies of schedule lengths for aircraft programs. First, Harmon et al. (1989) analyzed completion times for several portions of the development process for several third- and fourth-generation fighter and attack aircraft. Their paper identified 14 candidate variables (p. 138). Variables with strong explanatory power were

- program-specific parameter,
- airframe size (empty weight),
- contractor,
- prototypes (yes or no),
- supply-chain teaming, and
- production (rate and cumulative numbers; pp. 271–278).

On the other hand, Boyd and Mundt (1995) analyzed schedules for "heavy" aircraft (bombers, transports, tankers, and surveillance) over a long period (B-29 to C-17). Useful explanatory variables were

- date of engineering and manufacturing development (EMD) start,
- airframe size (maximum thrust, number of engines, and wing area),
- combat mission (yes or no), and
- prototypes (yes or no; pp. 142–144).

Interestingly, studies of similar program types undertaken relatively close in time (1989, 1995) by researchers from the same institution (the Institute for Defense Analyses) have commonalities and differences. The commonalities include aircraft size and prototyping (or not). For example, Harmon et al. (1995) estimated that having prototype aircraft can extend, or shorten, schedules in different phases of development (pp. 271–278), while Scott and Mundt's (1989) readers seem invited to conclude that prototyping extends program schedules (pp. 142–144).[10]

However, a striking indication for program individuality is the explanatory value that Harmon et al. (1989) found in "aircraft specific parameters" and specific contractor for each program.

All things considered, a somewhat ambiguous picture seems to emerge regarding the question of commonalities versus differences among programs. Harmon et al. (1989), finding the explanatory value from "program specific parameters" and "contractor," indicated the presence of characteristics peculiar to each program.

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[10] Prototyping is more likely to be observed in ambitious and complicated programs and is a method used to mitigate the inherently longer schedules of these programs. (If so, then prototyping is associated with longer schedules, but not a cause of longer schedules.) Among other things, this is a manifestation of the managed-process issue.

There is likewise a mixed picture from the airframe size parameters. Harmon et al. (1989) found capture airframe size with weight, while Boyd and Mundt (1995) operationalized size with engine thrust, the number of engines, and wing area.

Finally, differences in explanatory variables likewise indicate individual differences in acquisition programs. For example, Harmon et al. (1989) found supply chain characteristics and production variables useful, while they did not appear in Boyd and Mundt's (1995) reported model.

While it's reasonable to conclude from the examples that individual program characteristics are more important than commonalities, others find common themes. For example, the GAO (2010) undertook interesting case studies of program stability (defined as being "on track" concerning cost and schedule; p. 2). The study found the following characteristics common to the stable programs considered:[11]

- strong senior leadership support, disciplined PMs, and solid business plans that were well-executed (p. 9);
- strong PMs who shared key attributes (prior experience, communications skills, and willingness to report bad news; p. 14);
- capability needs that are addressed in achievable increments based on well-defined requirements (p. 16);
- mature technologies and production techniques (p.19); and
- funding stability (an "essential ingredient" for a successful program; p. 27).

Riposo et al. (2014) compiled an overview of factors causing schedule delays, distilled from the relevant literature (among other things). They grouped sources of delay in the literature into major categories: requirements development, generation, and management; managing technical risk; resource allocation; defense acquisition management; and "other" (Riposo et al., 2014, p. xi). Interesting findings included the following:

- Realistic cost and schedule estimates are essential in improving schedules (pp. 58–59).
- However, incentive structures can discourage realistic estimates—especially when competing for initial funding (p. 32).
- Several studies indicate good management of technical aspects (including technical risk) is likely the most crucial part of schedule improvement (p. 56). (Riposo et al. accordingly viewed "schedule improvement as an objective for acquisition managers" [p. 35, ch. 3]).[12]
- Factors external to the program itself can significantly influence schedules (p. 41).

Shackelford (2021) also undertook an overview of factors common to successful (or not) defense acquisition programs. Key factors cited were

- quality of communications and degree of trust (p. 4),
- requirements and funding stability (p. 9),
- sufficient production-representative test assets before MS C (p. 12),

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[11] The report equated "stability" with "success" (pp. 10–15, 27).
[12] A very interesting idea along this line is *optimal schedule length*, which depends in part on the characteristics of the individual program (Riposo et al., 2014, pp. 35, 47–48).

- good management decisions (p. 16), and
- strong, experienced program management (p. 21).

In our opinion, these are not idiosyncratic statements of general themes; we find differences in emphasis rather than differences in content. Accordingly, we essay the following synthesis of these three perspectives.

Likelihood of success is increased significantly through

- solid, executable plans with realistic cost and schedule estimates;
- disciplined requirements development;
- managing technical risk by avoiding technological leaps;
- strong, disciplined program management;
- effective communication and building trust among stakeholders; and
- resource and requirements stability (GAO, 2010; Riposo et al., 2014; Shackelford, 2021).

While this list is interesting and promising, we question how to measure the degree to which these factors are present in any given program. “Resource and requirements stability” seems straightforward. However, operationalizing these forms of stability is easier said than done: Is requirements (resource) stability something that’s present or not (a binary condition), or are there varying degrees of requirements (resource) stability for different programs?

The effects of program management performance have been investigated using proxy variables such as PMs’ experience and credentials—with mixed results. Apparently, the most readily accessible indicators are insufficient for the purpose.

Even more problematic is measuring the quality of communications and degree of trust. This suggests new approaches (which we discuss below).

What About Complexity?

Study the past if you would define the future.

—Confucius

Conspicuously missing from the major themes in the discussion is the matter of complexity. In this section, we examine the complexity of project management to relate that complexity to the critical variable of schedule intervals—defined as the time from one milestone to the next. The milestones (a start or finish of a phase in the development process) are determined by the DoD directives. The intent is to identify variables that help explain schedule behavior and provide DoD project managers the ability to manage time more effectively.

We build on a study that described and developed a methodology for extracting schedule data from selected acquisition reports (SAR; Pickar, 2018). Our current aim is to code and analyze the SARs database using computer-assisted qualitative data analysis (CAQDAS) software. This effort builds on a study started in 2018 that described and developed a methodology for extracting schedule data from the SAR databases (Pickar, 2018). The approach for this year’s effort includes the following:

- review past studies on SERs and weapon system development program complexity;
- identify reasons for delays in major programs; and

- perform a system development complex system classification assessment.

This analysis will (a) review the causes of schedule delays, (b) examine the concept of project complexity and relate that to schedule delays, (c) propose a methodology for measuring complexity in weapon systems development, and (d) explain how complexity assessment can assist in defining SERs. Central to any understanding of project/program schedule performance is an appreciation of past schedule performance. The delay and complexity factors discussed in this paper have occurred in all development programs.

Prior Research

Project performance (in both practice and research) is almost exclusively measured by adherence to cost and schedule estimates developed during the project planning process. Those estimates are often optimistic and almost always wrong. There are easily understandable reasons for schedule delays, but it is difficult to apply that knowledge to new programs.

Schedule Delays as Schedule Outcomes

Drezner and Smith (1990) explored the reasons for schedule delays in the case of 10 programs with MS I dates post-1970. The explanations included budget, funding, complexity, technical difficulty, and requirements stability. A list of these project delay factors is found in Table 3.

Table 3. Factors Influencing Schedules. (Drezner & Smith, 1990).

Factors Influencing Program Schedules of 10 Programs Post-1990
Competition at the prime contractor level
Concurrency, overlap in time and effort between the development and production phases of a program
Funding adequacy/stability
Existence of prototyping
Separate contracts for each phase of the program
Priority of the program to the service relative to other ongoing programs
External guidance such as Office of the Secretary of Defense or congressional direction, reviews, restrictions, and designations
Joint management with other agencies
Program complexity or interactions with agencies external to the program
Technical difficulty
Concept stability, or stability in mission, operational concepts, and doctrine
Contractor performance changes/contract changes
External events such as inflation, earthquakes, labor strikes, etc.
Major requirements stability
Program manager turnover
Rework
Design freeze

A more comprehensive examination of the reasons for delays in development was accomplished in 2018 by examining SARs from 1997 to 2017 (Pickar, 2018). A qualitative data analysis extracted the PM schedule comments and the reason and the duration of the delay. The total number of schedule records in the available SAR database was 3,969. The data used in this study are a subset of the SAR reports of 1,224 programs from 1997 to 2017. Each program potentially had between one and 20 entries (corresponding to the 20 years period and depending on when the program was initiated, whether breaches occurred requiring more frequent SAR, and whether any schedule changes were reported).

Table 4. Schedule Delay Factors, 1997–2017

Schedule Delay Factors
Administrative changes to schedule including updates to Acquisition Programs Baselines (APB), Acquisition Decision Memorandum (ADM) changes, as well as changes resulting from Nunn–McCurdy processes and program restructuring
Technical issues
Testing delays
Delay in the availability of critical capabilities/facilities (launch vehicle/testing facilities/initial operational test and evaluation [IOT&E] units)
Budget/funding delays
Delays attributed to the contractor
Delays because of rework
External events such as inflation, earthquakes, labor strikes, etc. **(force majeure)**
Delays due to contracting/contract negotiation/award

Explanations of the Delays

- Administrative changes include schedule updates because of acquisition program baseline (APB) and acquisition decision memorandum (ADM) changes and changes including program restructuring as a function of decisions driven by Nunn–McCurdy results and program restructuring.
- Schedule changes identified those changes reported because of acknowledgment of the actual date of occurrence. These changes are also the result of receiving approval documents from milestone decision authorities to change specific dates.
- Technical schedule changes are a result of specific setbacks in technological development.
- Testing delays include both the ability to meet scheduled test dates and technical issues discovered in the conduct of testing. When the testing found a technical issue, that technical issue was also counted as a technical problem.
- Explanations that produced no apparent changes in the schedule data reflect comments in the change explanation but do not produce an actual change in the schedule. Examples include cases of achievement of IOC/full operational capability (FOC) and redesignations of milestones driven by ADM decisions.

- Delay in the availability of critical capabilities/facilities results from weather delays, including satellite launches.
- Budget/funding delays are tied to specific notes on lack of budget, decrease in budget, or changes by Congress to the particular program.
- Delays attributed to the contractor result from construction and delivery delays and delays attributed to the delivery of subcontractor materials.
- Delays because of rework reflect both quality issues, where the budgeted work must be redone to make it functional, as well as the feedback/follow-on problems caused throughout the development.
- Force majeure are external events such as inflation, earthquakes, labor strikes, and so on.
- Delays due to contracting/contract negotiation stem from either problems in negotiation, delays in approvals for request for proposal (RFP) releases, modification to contracts, or delays in awarding contracts.

Understanding the challenges of estimating weapon system schedules requires examination of those factors that historically have led to increases in the schedules. While these studies identified factors that have contributed to increased time, they fail to provide a way to use that knowledge in the planning process to anticipate the necessary schedule increases. A second factor in understanding delays is the context of the delays, which is expressed as project complexity.

Schedule Estimating Relationships

In 1980, Smith and Friedman examined the concept of weapon system acquisition intervals. The study concluded that weapons systems schedules had increased development time and that Office of the Secretary of Defense (OSD) organization changes had little effect on schedule. The study also suggested various ways to decrease development time. In 1989, Harmon et al. examined schedule data to “provide methods for assessing the reasonableness of proposed acquisition schedules for tactical aircraft programs” (p. 259). Boyd and Mundt (1995) developed SERs for nontactical aircraft and introduced considerations of “factors that do not lend themselves to being measured using a continuous scale” (p. 133). These “schedule driver” factors included qualitative metrics such as funding stability and competition. Jimenez (2016) and Jimenez et al. (2016) developed a model to predict a program’s schedule based on program characteristics determined before MS B.

A 2018 RAND report developed SERs and provides a good menu of steps to conduct benchmarking (Light et al., 2018). The most recent examination of SERs was by Jardine et al. (2019). This study examined missile and radar data to create SER-specific data sets.

The data sets and processes developed for SERs have helped PMs plan and manage schedules and provide a valuable foundation. For the most part, those processes use relationships focused on measured intervals of weapon system development associated with budgetary data or physical attributes of different systems. These statistically sound findings provide high-level visibility into potential schedule intervals. We believe, however, that one of the significant contributors to schedule growth is the complexity of the systems being developed in the DoD. Therefore, it seems logical that consideration of complexity is a valuable avenue to explore.

Complexity

Complexity is the principal dynamic of 21st-century weapons system development and a measure of how difficult the management of the development of a weapon system could be.

Complexity in project management refers to those organizational, informational, and technical characteristics of the project and, by extension, the project management organization and the technical staff (Baccarini, 1996).

For the project manager, organizational complexity means hiring specialists—experts in a particular field—to address those demanding aspects of a complex system that require single-person focus. Specialization exercises a limiting function on the development, in that the specialists in a project organization can address only those issues in their specific area.

As a result, project management offices (PMOs) have increased in size to meet the needs of specialization—also resulting in an increase in complexity. This has entailed a corresponding decrease in the visibility over the entire project, a “can’t see the forest for the trees” analogy from the individual’s perspective. Thus, complexity has the potential of causing a decrease in efficiency in the execution of the project, which, among other things, could manifest as increased time.

Complexity directly affects management and decisions as the more complex the system, the more information is required. This leads to a more challenging management effort and the resultant choices required. The mixture of human-sociopolitical complexity found in weapons systems development offices further adds to this complexity (Atkinson, 1999; Pinto, 2000). Finally, complexity reduces the predictability of decisions made (Sargut & McGrath, 2011).

Definitions and explanations of complexity—managerial, engineering, and technological—abound (Baccarini, 1996; Sargut & McGrath, 2011; Whitty & Maylor, 2009; Williams, 2002). From the project management perspective, Baccarini (1996) identified two elements of complexity, organizational and technological. He further subdivides these functions into differentiation and interdependency. *Differentiation* refers to projects’ varied size and structure and the organizations that manage them, while *interdependency* describes the activities between these diverse elements (Baccarini, 1996).

Williams (2002) built on the Baccarini topology and defined project complexity as categories in two key areas, structural complexity and uncertainty. Figure 6 shows the Williams topology. Structural complexity results from the number of project elements—including the people, the organizations, and the technology—coupled with how these pieces interact with their interdependencies. This combination of interactions of the varied aspects is structural complexity. Structural complexity includes scale, connectivity, organizational structure, and development objectives. Size is about the magnitude of the acquisition system and its policies, bureaucracy, and hierarchy, including the private sector side of defense acquisition.

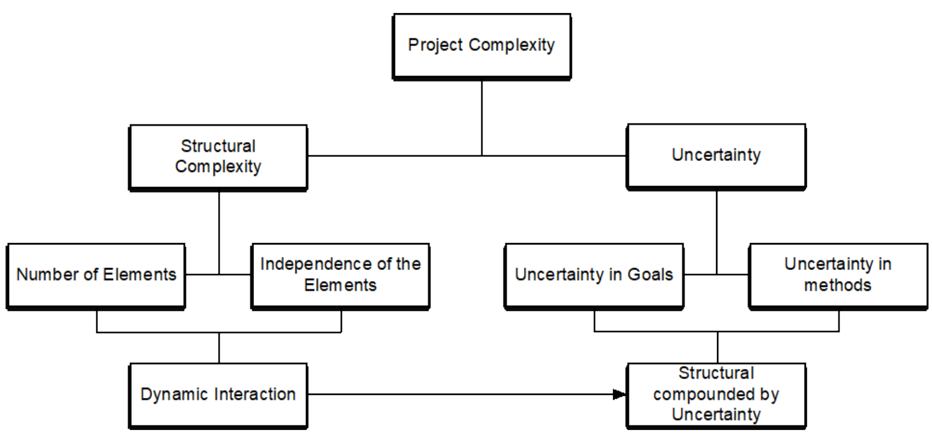

Figure 6. Project Complexity. (Williams, 2002, p. 58).

Connectivity acknowledges that the volume of staff actions between these organizations is significant and consists of both issues relating to managing ongoing development. The nature of the defense acquisition system influences the connectivity aspect of structural complexity. Since the technology development infrastructure (i.e., laboratories, research and development centers, and manufacturing) is, for the most part, privately owned, structural complexity also describes the network connectivity necessary for the system to function. Beyond the hierarchies, project organizations are major business entities directly controlling budgeting, spending, and, in most cases, the fee award to defense companies.

Project organizations are physically dispersed throughout the United States and overseas, further adding complexity. Finally, DoD project management is mirrored in the private sector by the contractor. A 2015 GAO study recognized the challenges of structural complexity in finding the reviews for some programs that include up to 56 organizations at eight levels. These structural requirements, reviews, and responding to information requests can add up to two years to the development time, significantly adding to the complexity of a development.

Uncertainty focuses on three significant areas: budget, technical complexity, and overall system objectives. Budget is a considerable concern and source of uncertainty in defense acquisition because of the year-to-year budget cycle and political considerations. Technological complexity is a fact of life in defense systems. As we develop systems, we learn more about the technologies and better plan for schedule and cost.

Sargut and McGrath (2011) identified three properties—multiplicity, interdependence, and diversity—essential to appreciate complexity. *Multiplicity* refers to the number of interacting elements or scale. This is like the Williams (2002) construct of structural complexity. *Interdependence* is the connectivity of different factors. And *diversity* is a measure of the difference in the elements (Sargut & McGrath, 2011).

Sheard and Mostashari (2009b) explained project complexity from the systems engineering perspective. The systems engineering standpoint acknowledges structural complexity but adds dynamic and sociopolitical complexity as factors influencing complex systems development (Sheard & Mostashari, 2009b). Dynamic complexity acknowledges the change-over-time of systems development. The project management system is in constant flux, whether a tactical response to a development problem or an administrative response to directives. This dynamic is a function of ongoing development's diverse and constantly changing aspects.

Sociopolitical complexity is the nexus between management, and the nonengineering human factors of policy, process, and practice of the system are most critical (Maier, 1995). Sociopolitical complexity also recognizes the politics of project management, starting with the budget process, through Congress, and back into the development organizations.

To provide an overall view and the elements of a complexity assessment tool, the complexity frameworks are summarized in Table 5. The resulting framework includes a typology of different kinds of complexity: structural, uncertainty, dynamic, sociopolitical, and overall system complexity.

Table 5. Project Management Complexity

Type	Subtype	Acquisition Management Example
Structural (Williams, 2002)	Size	Organization (number of people) Scope of work Contractor (size and number of people)
	Connectivity	Requirements organizations Industry organization Review processes (both programmatic and technical)
	Organizational	Stakeholder organizations Boundaries/different commands/different agencies Level of authority Congress
Uncertainty (Williams, 2002)	Budget	Funding
	Technical complexity	Variety of tasks Interdependencies between tasks
	Objectives	System requirements
Dynamic (Sheard & Mostashari, 2009a)	Short-term	Daily problems Personnel changeover Engineer shortage Materials failures Short requirement dynamics Rework
	Long-term	Changing budget Environment
Sociopolitical (Maier, 1995)	Human dimension	Personnel changeover Change and change management Regulations/policy changes

Measuring Program Complexity

Describing complexity is simpler than devising a means to measure it. Using the complexity breakdown above, the next step in this research is to build an assessment tool to classify selected existing weapons systems. Magee and de Weck (2004) developed a method to classify complex systems. This approach was a top-down, bottom-up review to identify and distinguish between complex systems and engineering systems. While their purpose was to differentiate complex engineering systems from traditional engineering, some elements of this approach can help classify defense systems. Similarly, Thamhain (2005) believed a tool that can determine project complexity can be valuable to the project manager as a comparative measure. Researchers in architecture and construction have also developed tools to measure complexity (Dao et al., 2016; Sinha et al., 2006).

Bosch-Rekveldt et al. (2011) developed one of the more refined studies on complexity metrics. The technical, organizational, environmental (TOE) framework consists of 40 elements shown in Table 6.

Table 6. Technical, Organizational, and Environmental Framework

Bosch-Rekveldt et al. (2011) Complexity Metrics	
Number of goals	Size of project team
Goal alignment	Size of site area
Clarity of goals	Number of locations
Scope largeness	Resource and skills availability
Uncertainties in scope	Experience with parties involved
Quality requirements	HSSE awareness
Number of tasks	Interfaces between different disciplines
Variety of tasks	Number of financial resources
Dependencies between tasks	Contract types
Uncertainty in methods	Number of different nationalities
Interrelations between technical processes	Number of different languages
Conflicting norms and standards	Cooperation JV partner
Newness of technology (worldwide)	Overlapping office hours
Experience with technology	Trust in project team
Technical risks	Trust in contractor
Project duration	Organizational risks
Compatibility of different project	Number of stakeholders
Political influence	Variety of stakeholders' perspectives
Size in engineering hours	Dependencies on other stakeholders

Table 7 takes some of the complexity metrics discussed and provides an example of a tool to measure the complexity of a weapons system development program during the planning process and when using complexity to develop SERs. The tool uses the metrics shown in Tables 3 and 4 and provides a menu for the PMO to assess complexity.

Table 7. Complexity Score Card

Complexity Assessment Tool						
Parameter	Low <25 pts	Medium <50 pts	High <75 pts	Very High <100	Weight	Total Complexity Index
Size	$<10M	$10–99M	$100–500M	>$500M		
Project Duration	<1 yr	<3 yr	<7 yr	>7 yr		
Ratio Budget/ Duration						
Organizational	PdM	PM	PM	PEO		
Budget	Yes	Some	Little	First Time		
Risk	Low	Med	High	Very High		
Technical Complexity	Low	Med	High	Very High		
Technological Maturity	Very High	High	Med	Low		
Dynamics	No	Little	Some	Yes		
Human Dimension	Component	Subsystem	System	SOS		
Number of Contr/Subs	<3	< 5	< 7	>7		
Software						
Total						

Complexity Leads to Delays

Table 8 shows the relationship of project complexity to the identified schedule delay factors. When more than one factor is present, they are listed in order of impact. Examination of Table 8 almost forces one to ask the question, *Which comes first, the complexity issue or the delay?* The answer to that question depends on the desired response. The complexity factors would be used to assess programs during the planning process to allow a for macro-level estimate using SERs. Similarly, the delay factors would also be used during the planning process as questions to be answered during the walk-through of the work breakdown structure. Together the elements provide a tool to be used during program execution.

Table 8. Combined Complexity and Delay Factors

Complexity Factors	Delay Factors
Structural	Competition at the prime contractor level
Sociopolitical, Dynamic	Administrative changes
Structural, Dynamic	Concurrency, overlap in time and effort between the development and production phases of a program
Uncertainty, Structural	Budget/funding delays, funding adequacy/stability
Uncertainty	Existence of prototyping
Structural	Separate contracts for each phase of the program
Structural	Priority of the program to the service relative to other ongoing programs
Structural	External guidance such as OSD or congressional direction, reviews, restrictions, and designations
Structural	Joint management with other agencies
Uncertainty	Technical difficulty
Uncertainty	Concept stability, or stability in mission, operational concepts, and doctrine
Uncertainty	Contractor delays
Dynamic	Delays due to contracting/contract negotiation/award delays
Uncertainty	External events such as inflation, earthquakes, labor strikes (force majeure)
Uncertainty	Major requirements stability, design freeze
Sociopolitical, Uncertainty, Dynamic	Program manager turnover
Uncertainty, Dynamic	Testing delays
Uncertainty, Dynamic	Rework
Uncertainty, Sociopolitical	External events such as inflation, earthquakes, labor strikes, etc.

Schedule Delays, Complexity, and Historical Learning

A development project or program is a dynamic system with feedback loops. Invariably, decisions taken to address one problem have an impact on or create new problems. We believe the schedule and complexity factors discussed in this paper can be effectively applied to the analysis and development and eventual execution of the schedule. Finally, an appreciation of the historical performance of development programs can and should be used to better inform the development of weapons system development schedules.

While the case for complexity as a significant schedule driver seems compelling, “complexity” is complex to define and difficult to measure. Further, a “Total Complexity Index” is appealing, but reducing a vector whose components are challenging to quantify to a scalar quantity is imposing.

There have been some interesting and valuable efforts to find observable proxies for complexity. For example, physical complexity as defined by the density of equipment within a platform (Grant, 2008; Terwilliger, 2015) has been studied as a cost driver. Likewise, "virtual" complexity, as measured perhaps by lines of software code, is very promising. However, these capture only a few of the total-complexity vector described in Table 8.

Summary and Concluding Comments

Our primary purpose in this effort has been to build a case for new empirical sources and methods for acquisition schedule estimation. We have tentatively identified CAQDAS software.

We got there by considering the inherent difficulties in schedule estimation: "incidental" factors, variation in outcomes due to program management decisions, and the incentives endemic to source selections that reward unrealistic estimates (cost, schedule, and performance). We reported evidence from the literature that supported both common and idiosyncratic schedule drivers across programs.

Support for the common-factors perspective comes from "meta-studies" of program outcomes that can be reduced to several major program themes (such as quality of communication, management competence, and degree of trust between the major players).

While these lines of inquiry are interesting and promising, defining, operationalizing, and measuring are difficult (at best) using methods within the current state of practice.

One useful next step in advancing the art and science of schedule estimation is new forms of data analysis. Fortunately, several tools have recently emerged for analyzing quantitative and qualitative data. We view developments in qualitative data analysis to be more promising—particularly concerning variables (such as quality of communication) that are difficult to map to real numbers.

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