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OCCASIONAL PAPER

On Prototyping

Lessons from RAND Research

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Prepared for the Office of the Secretary of Defense

Approved for public release; distribution unlimited

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The research described in this report was prepared for the Office of the Secretary of Defense (OSD). The research was conducted in the RAND National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense, the Joint Staff, the Unified Combatant Commands, the Navy, the Marine Corps, the defense agencies, and the defense Intelligence Community under Contract W74V8H-06-C-0002.

Published 2009 by the RAND Corporation
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Preface

Today's defense environment is placing growing pressure on defense policymakers to be nimble and adaptive, particularly with respect to acquisition systems and processes. This occasional paper is one in a series drawing upon the expertise of core RAND Corporation staff to explore issues and offer suggestions on topics that are likely to be of critical importance to the new leadership: the use of competition, development of novel systems, prototyping, risk management, organizational and management issues, and the acquisition workforce. The papers are designed to inform new initiatives for markedly improving the cost, timeliness, and innovativeness of weapons systems that the Department of Defense (DoD) intends to acquire.

This paper reviews four decades of RAND research on the uses of prototyping and identifies the conditions under which prototyping activities are most likely to provide benefits. We conclude that, although the available evidence is somewhat mixed overall, the historical record does suggest some of the conditions under which prototyping strategies are most likely to yield benefits in a development program. These conditions include ensuring that prototyping strategies and documentation are austere, not committing to production during the prototyping phase, making few significant design changes when moving to the final configuration and maintaining strict funding limits.

This study was sponsored by the Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (OUSD–AT&L) and conducted within the Acquisition and Technology Policy Center of the RAND National Defense Research Institute, a federally funded research and development center sponsored by the Office of

the Secretary of Defense, the Joint Staff, the Unified Combatant Commands, the Navy, the Marine Corps, the defense agencies, and the defense Intelligence Community.

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On Prototyping

Introduction

Acquisition policy and practice reflect the recurring theme that prototyping as part of weapon system development can improve program outcomes. Specifically, prototyping is widely believed to reduce cost and time; allow demonstration of novel system concepts; provide a basis for competition; validate cost estimates, design, and manufacturing processes; and reduce or mitigate technical risk.[1] A mandate for competitive prototyping has periodically been included in revisions to the DoD 5000 series of regulations governing the defense acquisition system. The most recent revision to DoD Instruction 5000.02 (December 2008, p. 17) contains the following mandate:

> The TDS [Technology Development Strategy] and associated funding shall provide for two or more competing teams producing prototypes of the system and/or key system elements prior to, or through, Milestone B. Prototype systems or appropriate component-level prototyping shall be employed to reduce technical risk, validate designs and cost estimates, evaluate manufacturing processes, and refine requirements.

This paper reviews four decades of RAND research on the uses of prototyping in DoD in order to draw lessons that practitioners can apply

[1] See, for instance, Young, 2007.

as they respond to the new emphasis on prototyping in DoD acquisition policy.[2] RAND's research on this topic has been periodic, reflecting the waxing and waning of DoD interest in prototyping. We make only limited use of prototyping-related studies outside of RAND research; these studies have also been episodic in their coverage of prototyping.

In this paper, we first define prototyping and discuss the potential benefits commonly attributed to it. We then review historical analyses to determine how well those potential benefits are supported by experience. Last, we make explicit some of the more important thematic lessons and specify the conditions under which prototyping is most likely to yield expected benefits.

What Is Prototyping?

In general, prototyping is a set of design and development activities intended to reduce technical uncertainty and to generate information to improve the quality of subsequent decisionmaking. Although the term "prototyping" captures a wide range of activities, all prototyping has several elements in common, including the design and fabrication of one or more representative systems (hardware or software) for limited testing and demonstration prior to a production decision. The prototype itself is the article being tested.

Prototyping is a conscious strategy to obtain certain kinds of information to inform specific decisions.

> A prototype is a distinct product (hardware or software) that allows hands-on testing in a realistic environment. In scope and scale, it represents a concept, subsystem, or production article with potential utility. It is built to improve the quality of decisions, not

[2] Of approximately 30 reports and papers reviewed, eight were specifically focused on prototyping; the others touched on aspects of prototyping in the course of exploring other acquisition issues, such as development strategies more generally or cost and schedule issues.

> merely to demonstrate satisfaction of contract specifications. It is fabricated in the expectation of change, and is oriented towards providing information affecting risk management decisions. (Drezner 1992, p.9)

In other words, prototypes are distinct from full-scale, final configuration, production-representative test articles the main purpose of which is to verify that performance requirements have been met and the program is ready to move into the production phase. The expectation that prototyping will lead to change implies that a prototype is intended as a vehicle to learn something about the system's technology or concept that will inform subsequent decisions. The prototype itself does not have to be a fully configured production article to accomplish this purpose.

Prototyping can take many forms. It can be conducted at both the system and subsystem level. It can include competition (e.g., two or more teams designing, fabricating, and testing a representative system in the context of a source-selection decision) or just a single organization experimenting with a novel concept or new technology. Some developmental activities (i.e., experimentation, system concept and technology development, demonstration and validation) are often not labeled as prototyping, but the nature of the activities planned and accomplished is consistent with prototyping. For example, Advanced Technology Demonstration (ATD), Advanced Concept Technology Demonstration (ACTD), and Joint Concept Technology Demonstration (JCTD) projects involve specific kinds of prototyping activities.[3]

Prototypes can be part of the early stages of a Major Defense Acquisition Program (MDAP), part of a series of related efforts (e.g., the X-plane series of experimental aircraft)[4] or stand-alone projects.

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[3] See Drezner, 1992 for a full exploration of the different kinds of prototyping strategies.

[4] The X-planes were experimental aircraft (from the X-1 in 1946 to the X-53 in 2002) designed to expand knowledge of aerodynamics and air vehicle and engine design. Individual projects were run by combinations of NASA, the U.S. Air Force and U.S. Navy, and industry. The X-1 was the first aircraft to break the sound barrier. The X-15 achieved hypersonic (Mach 6) manned flight. Other projects demonstrated different wing or body configurations. The first unmanned combat air vehicles (X-45 and X-47) were industry projects intended to demonstrate a new capability.

However, it is important to note that prototyping alone does not constitute a full weapon system development program. When incorporated into an MDAP, prototyping should be used together with design analysis, empirical testing, modeling and simulation, and "other methods of reducing technological uncertainty" (Perry, 1972, p.41) because these other methods produce information that prototyping alone will not; such approaches are complementary in the context of an MDAP. When prototyping is done outside of an MDAP, the transition and transfer of technology and information becomes an important practical issue affecting the value of the prototyping effort. Unlike an MDAP, which has a constituency who ensure the political and budgetary support necessary to move the project forward, an ATD or ACTD program does not necessarily have the support of the military service for which it ultimately may be intended.[5]

Some weapon types are generally too costly to prototype at the system level (e.g., large naval surface combatants and complex satellites). In such cases, *subsystem* prototyping is a cost-effective alternative for reducing uncertainty. For instance, the DD(X) program (now called DDG 1000, the Navy's newest guided missile destroyer) successfully used a series of Engineering Development Models (EDMs)—that is, prototypes of critical subsystems, such as the hull form, advanced gun and its munitions, composite deck house, peripheral vertical launch missile system, and radars, among others—to reduce technical risk and refine subsystem design.[6]

Although the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD (AT&L)) defined prototyping activities as occurring prior to Milestone B (Young, 2007, p.1), and the recently revised DoD acquisition policy, quoted above, places prototyping

[5] The Predator and Global Hawk unmanned aerial systems (UAS) programs are good examples of this issue and also demonstrate that the issue can be resolved. See Thirtle, et al., 1997; Drezner and Leonard, 2002.

[6] Several U.S. Government Accountability (GAO) reports discuss the role of the EDMs in the overall program, including GAO-07-115 (November 2006), GAO-05-924T (July 2005) and GAO-04-973 (September 2004). Full citations are in the Reference list at the end of this paper.

in the technology development phase (before Milestone B and the start of engineering and manufacturing development), prototyping as defined in this occasional paper is not confined to any particular acquisition-process stage of the development process. Moreover, our definition covers a broader range of activities and is not confined to a particular funding mechanism or program type.

What Are the Expected Benefits of Prototyping?

Theoretical arguments heavily favor the use of prototyping as part of weapon system development, or more specifically, as a way to demonstrate novel concepts and resolve technological uncertainty. The expected benefits, as listed below, are largely related to the design, fabrication, and test of the prototype. However, prototyping can be applied in any situation in which improved information through demonstration would be of value. Less traditional applications include prototyping specific management techniques or policies, or prototyping the support and maintenance concepts for a weapon system.

Given DoD's recent competitive prototyping policy, it is useful to compare DoD's list of expected benefits with similar sets of benefits and skepticisms generated in prior research by RAND and others. DoD policy lists the following primary benefits:

- Reduce technical risk.
- Validate designs.
- Validate cost estimates.
- Evaluate manufacturing processes.
- Refine requirements.

The policy directive on competitive prototyping (Young, 2007, p.1) listed these as well as a set of secondary benefits:

- Exercise and develop government and industry management teams.
- Provide an opportunity to develop and enhance system engineering skills in both government and industry.

- Attract a new generation of scientists and engineers to DoD and the defense industry.
- Inspire and encourage students to embark on technical education and career paths.

The expected benefits of a particular prototyping strategy for an individual program will not necessarily include all of these potential benefits. Front-end planning activities should identify which benefits are being targeted and then design a prototyping strategy to provide those specific benefits. In other words, prototyping involves a conscious strategy to obtain certain kinds of information to inform specific decisions. In the remainder of this section, we examine expected benefits of prototyping in more detail.

Reduce Technical Risk. Reducing technical risk is an important benefit of prototyping strategies. By building and testing representative items, prototyping can identify and resolve technical uncertainty; demonstrate technological feasibility; advance technological maturity; refine system requirements and validate the system design to satisfy those requirements; and provide information to improve estimates of cost, schedule, and performance.

Prototyping can resolve known technical uncertainties—and identify uncertainties that were not anticipated ("unknown unknowns").

An important aspect of risk reduction is the discovery of technical uncertainty not anticipated by the design engineers nor predicted by design analyses or prior experience with analogous technologies. In other words, prototyping can address both the "known unknowns" and the "unknown unknowns," sometimes yielding unexpected (unlooked-for) benefits. For instance, testing of the Global Hawk (an unmanned aerial vehicle) resulted in the development of an unplanned for capability (in-flight retasking)[7] not envisioned at the design stage (Drezner and Leonard, 2002).

[7] That is, redirecting the air vehicle so onboard sensors can capture targets of opportunity.

Validate Design and Refine Requirements. Prototyping strategies are fundamentally about using information generated during design, fabrication, and testing activities to inform subsequent decisions regarding cost–performance tradeoffs, source selection, validation of technologies, readiness to move into subsequent program phases, and force structure. Relatively more and higher-quality information can be generated during prototyping than in alternative development approaches that rely more heavily on "paper" design activities or, more recently, on computer-aided design, modeling, and simulation. Presuming that the information that is generated is used appropriately, the quality of those decisions should improve.

Validate Cost Estimates. While prototyping may not truly validate cost estimates (most prototyping occurs early in development, and the prototypes themselves are not the full-production configuration), it may improve the quality of those estimates. Other benefits discussed—such as reductions in technical risk, more mature technology, refinement of requirements based on demonstrated feasibility, and validation of key system design elements—should enable a more accurate cost estimate.

Evaluate Manufacturing Processes. A prototyping strategy can be designed to evaluate or improve manufacturing processes. Achieving this potential benefit would require making elements of the manufacturing process (i.e., tooling, material use and handling, production process layout) an explicit part of the prototyping strategy. There is an important tradeoff here: Including the full set of production considerations in a prototype designed, fabricated, and tested as part of technology development would likely add cost and time to the effort. Nevertheless, the construction of the prototype itself will provide some valuable insights to evaluate and improve production processes.

The expected secondary benefits identified by DoD policy (listed above) relate either to the development and maintenance of program management, system engineering and other technical skills, or to the development and recruitment of the next generation of defense program managers, scientists, and engineers. RAND research has addressed the former but has not addressed the latter.

Maintaining Workforce Skills and Experience. Prototyping helps to sustain industry design capabilities through design, fabrication, test, and redesign activities. Prototyping provides a more complete experience for a design team. As past RAND reports have noted:

> To be really good at designing combat aircraft, members of a design team must have had the experience of designing several such aircraft that actually entered the flight-test stage. Paper designs and laboratory development are important, but they are not a substitute for putting aircraft through an actual flight-test program. (Drezner et al., 1992, p. 16)
>
> If experience is as important as might be inferred from the historical record, clearly the DoD needs to consider options that will help maintain experience levels during long periods when no major R&D programs are under way. Such a strategy could focus on prototyping or technology demonstration. (Lorell, 1995, p. 65)

Similarly, prototyping activities may provide the government workforce with hands-on experience in program management, system engineering, testing, and other skill sets necessary for the conduct of a successful acquisition program.

RAND research suggests additional potential benefits from prototyping not explicitly listed in DoD policy, including the following.

Reduction in Fielding Time. Prototypes can demonstrate the military utility of a system concept or technology, enabling relatively shorter time spans from concept definition to fielding of an operationally useful capability. This applies to prototyping both as part of a MDAP (e.g., the YF-16 Lightweight Fighter, which led to the F-16A/B) or stand-alone, pre-MDAP programs (e.g., fielding the ACTD configuration of Global Hawk during the initial stages of the wars in Afghanistan and Iraq).

Enhanced Competition. Prototyping strategies can enhance competition among two or more firms or teams by requiring actual demonstration of proposed capabilities. Competitive prototyping has been used extensively, for example, in the history of fighter and bomber aircraft development, often demonstrating the value of new designs or technologies and giving government source-selection authorities increased confidence in their decisions (Lorell, 1995). The testing of competitive prototypes can provide better information than design proposals alone.

Improved Research and Development (R&D) Efficiency. A prototyping strategy can also be more efficient, providing an opportunity for "obtaining information sooner or more cheaply than by other means" (Perry, 1972, p.41).

Hedging Your Bet. Some prototyping strategies can offer a hedge against other kinds of uncertainty beyond technical uncertainty. For instance, a competition with two or more system designs provides a hedge against the nontechnical failure of one. For example, technology demonstration prototyping strategies—in which system concepts are tested outside of established programs—can provide a hedge against changing or emerging threats. Within DoD, these programs are usually ATDs, ACTD, JCTDs, or similar programs.

Skepticism about the benefits of prototyping is less common than enthusiasm, but it does exist. The counterarguments revolve around two notions—that changes in performance requirements (capabilities) and duplication of effort reduces the value of prototyping. The first notion is that a prototype phase does not really reduce uncertainty (or risk) because decisionmakers will be unable to resist the temptation to modify system performance specifications to capitalize on recent technological advances. Incorporating that new technology will increase risk since those changes were not part of the prototype phase, thus reducing the value of prototyping. The second notion is that:

> a comprehensive design effort is unavoidable in any case and . . . pausing . . . to construct a prototype merely lengthens the program and increases its cost without securing any equivalent benefits. The argument is that engineering problems will be encountered in both cases, but that careful study and design analysis will identify

> them earlier than will prototype construction. Furthermore, it is widely believed that the construction of a prototype encourages designers to overlook compatibility problems, to create something that is less than a system and that must be substantially reengineered before it is ready for production. (Perry, 1972, p.10)

The counterargument about changing requirements after prototype testing revolves around the notion that significantly changing the design of a system reduces the value of the information obtained through prototyping. This may be a valid concern at the extreme, where design changes subsequent to prototype testing result in a completely different configuration. However, one could also argue that the prototyping experience resolves uncertainties associated with the initial requirements, a nontrivial contribution to the development program even if requirements are changed somewhat or new capabilities added. To an important degree, prototyping is intended to result in design changes based on lessons from testing. It may also identify flawed or infeasible requirements, to the benefit of the program. Prototyping does not resolve all uncertainties associated with a system or technology concept, but rather only those it was designed to resolve and perhaps some "unknown unknowns" that become apparent during testing.

Skeptics contend that subsequent changes to performance requirements and duplication of effort reduce the value of prototyping.

The second counterargument—that the prototyping effort is duplicative and produces little unique knowledge informing the detailed design phase—is less valid. For instance, even with advances in computational fluid dynamics, wind tunnel testing and live flight testing of aircraft configurations are still required for designs that push the edges of known and demonstrated performance, as many military systems do.[8] Demonstrations in realistic operational environments

8 For a discussion, see Antón, et al., 2004, both TR-134-NASA/OSD and MG-178-NASA/OSD.

consistently produce information about system performance not otherwise obtainable, and fabrication of a prototype certainly exercises skills that design activities alone cannot. Prototype testing also enables identification of any unknown or unexpected performance behaviors or technical risk.

Historical Evidence Is Mixed

RAND's past research on the topic of prototyping includes both (1) statistical analyses of large databases containing information on both prototyping and nonprototyping programs and (2) case studies (in varying degrees of detail) of prototyping programs, with comparisons to nonprototyping programs. The programs studied in this body of research include the following, among others:

- Century-series fighters (F-100 through F-105)
- AX close air support/attack aircraft (YA-9 versus YA-10)
- Lightweight Fighter (YF-16 versus YF-17)
- Advanced attack helicopter (YAH-63 versus YAH-64)
- Utility transport helicopter (UH-60 versus UH-61)
- F-117 (Have Blue)
- Advanced Medium-Range Air-to-Air Missile (AMRAAM)
- Predator unmanned aerial system
- Global Hawk unmanned aerial system
- DarkStar unmanned aerial system
- F/A-18 and F/A-22 fighter aircraft

Overall, evidence from this body of work is somewhat mixed regarding the benefits of prototyping. However, many factors affect program outcomes independent of prototyping; thus, teasing out the relative effect of prototyping is challenging.

In general, we would expect to find that programs incorporating prototyping would have less cost growth on average because the baseline cost estimate would benefit from the risk reduction and information on cost–performance tradeoffs obtained through early prototyping.[9] Findings from numerous case studies support this expectation, as indicated in the following examples:

> The experience of the Air Force in buying “soft tooling” prototypes, including the two XF-104s, suggests that under appropriate conditions an airframe very useful for flight testing of both basic designs and readily available subsystems might be obtained for about 60 percent of the cost of a “hard tooled” prototype. And of course it becomes available much sooner. (Perry, 1972, p. 39)[10]

> There is some evidence that, on average, cost growth of prototyped programs is less than that of conventional acquisition programs, and the magnitude of such “savings” is much greater than the direct cost of the prototype phase. (Smith et al., 1981, p. 35)

However, a statistical analysis conducted in the early 1990s of the factors affecting weapon system cost growth—including the effect of prototyping on cost outcomes—found no easily discernible patterns in the data (see Figure 1).[11] If anything, the data appeared to indicate that prototyping programs had higher cost growth than nonprototyping programs, with average cost-growth factors of 1.29 and 1.19,[12] respectively (there were 30 observations in both groups of programs).

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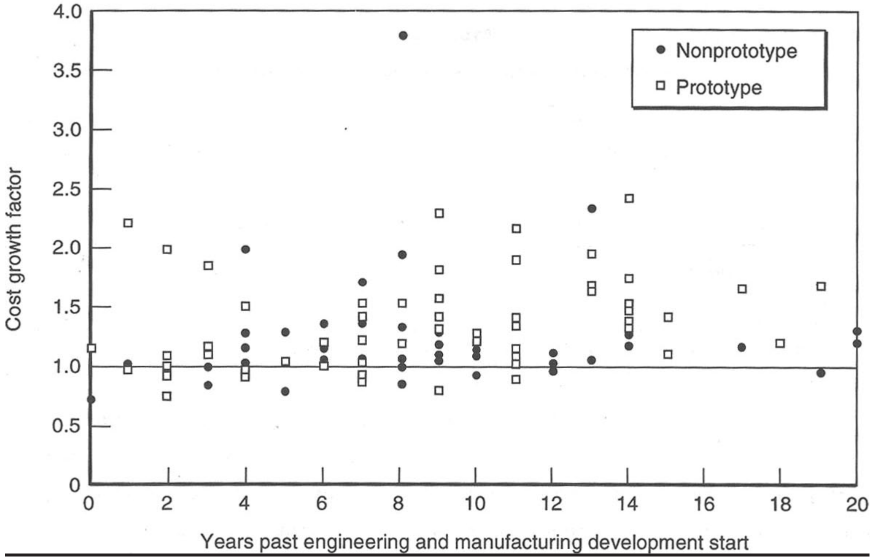
[9] In this paper, cost growth was measured from the Development Estimate baseline established at Milestone II (now called Milestone B) using quantity adjusted data from the Selected Acquisition Reports (SARs). Though this analysis is 15 years old, RAND has continued to update the database. More recent analyses, while not explicitly addressing prototyping, are consistent with the basic findings in the earlier report and do not provide any indication that results on prototyping might change. See also Arena et al., 2006; Younossi et al., 2007; and Bolten et al., 2008.

[10] “Soft tooling” consists of the temporary set of tooling used to construct a limited number of prototypes. Such tools (molds for shaping materials, presses and drills, wire fitting, workstations, et cetera) may adapt general purpose or existing tools, or may even be made of wood. “Hard tooling” refers to the final set of tools used for longer production runs.

[11] Drezner et al., 1993.

[12] Cost-growth factors translate directly to percentages: an average cost-growth factor of 1.29 indicates that on average, the programs in that group had 29 percent cost growth above their baseline estimates.

Figure 1
Cost-Growth Factor Distribution of Prototyping and Nonprototyping Programs, circa 1993



SOURCE: Drezner et al., 1993, p. 37 Figure 5.1.

This counterintuitive result can be partially explained by the fact that the programs in the prototyping group were, on average, older and smaller than the programs in the nonprototyping group: Relatively older (more mature) programs (measured as years past the baseline cost estimate) tend to have higher cost growth, and relatively smaller programs (measured in inflation adjusted dollars) also tend to have higher cost growth. However, when we compared programs in which the prototyping phase occurred earlier—prior to Milestone II (when the program baseline was established)—to programs in which the prototyping phase occurred after the milestone, the expected

A statistical analysis suggested that programs that use prototyping do not show less cost growth—unless prototyping occurs prior to Milestone II.

result obtains: programs with earlier prototyping had an average cost-growth factor of 1.23 versus 1.37. This result indicates that using the information generated during early prototyping may improve subsequent cost estimates.

Another widely held belief is that spending relatively more time prior to Milestone B (formerly, Milestone II) in planning and technology demonstration activities (including prototyping) would result in less schedule slip. A study that examined in detail the factors affecting schedule slip of 10 MDAPs did not find evidence to support this hypothesis (Drezner and Smith, 1990); however, several other studies did. For example:

> There is no evidence that the introduction of a prototype either delays the availability of the production article or increases the cost of development. (Perry, 1972, p.45)

> The histories of attack and fighter aircraft developed by the Navy and the Air Force since 1950 indicate that introducing a prototype makes little difference in the total development time. Furthermore, if a prototype program can be started earlier than could an equivalent full-scale development program (as was certainly the case with the LWF program), then use of a prototype phase may actually lead to an earlier fielding date. (Smith et al., 1981, p.35)

In addition, one study that compared the development strategies and outcomes of two programs using differing prototyping strategies found evidence that prototyping benefited both programs:

> Another major difference between the two programs was that the YF-16 was a true prototype of the F-16 flight vehicle, thereby providing a considerable start on the overall system design. Conversely, the Have Blue program was a technology demonstrator and provided almost nothing toward the detail design of the F-117. On that basis, we would expect that, measured from EMD start, the F-117 schedule would have been extended, compared

> with the F-16, while in fact the time to first delivery was about the same for both programs. This suggests that the F-117 program was relatively short. (Smith et al., 1996, p.30)

Though it was a subscale technology demonstrator, Have Blue did validate key aspects of the F-117 design, providing increased confidence to decisionmakers. The two programs had very different prototyping strategies, but both appear to have derived important benefits, including the generation of information that facilitated a relatively shorter development phase. Prototyping activities provide benefits by generating information not otherwise attainable.

One possible explanation for these mixed results concerns the exact metric used in the analysis. By their nature, prototyping strategies generate useful information applicable mainly to a particular design, technology, system concept, or other engineering challenge. The information would be expected to improve decisionmaking or estimates for systems closest to the prototype's design. For instance, when measuring the effect of prototyping on the accuracy of cost, schedule, or performance estimates, initial estimates of cost, schedule, or performance should be compared only to the version of the system that is based on the prototype. Applying this principle to F-16 program outcomes, discussed in the last case study above, only the F-16A/B models should be considered in the analysis; the F-16C/D models came much later, and cost, schedule, or performance estimates were not likely affected by the prototyping experience of earlier years. Unfortunately, this level of discrimination in a study is difficult to achieve due to the limits of available data and so has been undertaken only infrequently.

Perhaps more importantly, many factors other than prototyping affect program outcomes. Such factors include infeasible requirements, requirements change, budget instability, and underestimation of technological maturity. As discussed above, prototyping can be designed to address the feasibility of requirements and technological maturity, but any benefits in these areas can be overwhelmed by other factors. The F-22, the JSF (F-35), and Global Hawk all included prototyping strategies of one form or another that appeared quite useful at the time, yet all three programs have incurred high cost growth and schedule slip.[13] This suggests that prototyping is not a panacea for solving all of the problems of the acquisition process.

In general, evidence from case studies tends to support the notion that prototyping strategies are beneficial as part of weapon system development in some circumstances. Prototyping does help discover technical risks and thus can reduce technical uncertainty. Prototyping does produce information useful in validating design choices, refining requirements, and improving the quality of cost estimates. However, results from both case studies and statistical analyses suggest that the impact of these benefits on cost, schedule, and performance outcomes can be overwhelmed by other factors affecting programs.

Conditions That Favor Prototyping

Though the available evidence is somewhat mixed overall, the historical record does suggest some of the conditions under which prototyping strategies are most likely to yield benefits in a development program. Successful application of prototyping strategies in the future requires either creating these conditions or ensuring that they exist to the extent possible.

Results Are Used to Inform Key Program Decisions. If the information generated from prototyping activities is not used to inform key program decisions (including final design, technologies and capabilities to include in the initial production system, planning for subsequent technical and engineering activities, and cost and schedule estimates), then there would be no reason to expect benefits. If early testing of a prototype indicates that available technology is not yet mature enough to confidently predict that system performance requirements will be met, then pushing ahead in that program without easing requirements and performance expectations to match demonstrated technological

[13] See Selected Acquisition Reports for the programs. See also several GAO reports.

maturity will result in significant cost growth, schedule slip, and performance shortfalls.

The Prototype Is Designed to Demonstrate the Critical Attributes of the Final Product in a Realistic Environment. Prototypes should be designed to test the key performance attributes about which there is the greatest uncertainty and which are expected to enable mission accomplishment. This includes major subsystems that affect not only performance, but also design (such as the integration of a specific engine, airframe configuration, and sensor package in an aircraft). Prototyping strategies appear to yield benefits when they are focused on specific challenges or designed to generate specific kinds of information to inform specific kinds of decisions

Prototyping is more effective when critical performance attributes are tested in a realistic environment.

Prototyping Strategies and Documentation Are Austere. There is some evidence, particularly from the many past aircraft prototypes, that an austere program is an important attribute of a successful application of prototyping. Prototyping should include only the minimum necessary requirements specified and only the minimum documentation required to analyze test results and capture lessons learned from the activity. In general, this means focusing the prototype itself on a few key uncertainties, keeping noncritical technical standards to a minimum, and focusing associated program documentation on the prototyping activity. It also means the use of relatively small teams of highly capable people with appropriate decision authority regarding the prototyping activity, minimal requirements for status reporting, and minimal external interference (e.g., externally imposed design changes) with the team's activities. This gives the design team more flexibility to make the inevitable cost–performance trade-offs, such as deciding not to include demonstration of a second-order capability due to cost considerations.

Sustainment issues, technical data requirements, production planning, and tool design are commonly not addressed in an austere prototyping strategy. However, these issues could be addressed through a phased or incremental prototyping strategy in which two sets of prototypes are designed and tested—the first addressing critical technical performance issues and the second addressing support issues. While possible in theory, we are not aware of any program that has attempted such an approach.

There Should Be No Commitment to Production During the Prototyping Phase. Prototyping is experimental in nature, and failure is a possible outcome in the sense that the desired capabilities could not adequately be demonstrated in a realistic environment and at a reasonable cost. Such an outcome would be strong evidence that the requirements need to be relaxed and additional technology development and maturation is needed. Perhaps the program based on the system concept should be deferred indefinitely until certain critical technologies are demonstrated. Such decisions are much harder to make if a commitment to production has already been made, either implicitly or explicitly. Production requires that a whole other set of issues be addressed (force structure, sustainment options, significantly increased budgets, et cetera).

Prototyping may lead to tough decisions that are best made before committing to production.

No Additional Requirements Are Added or Performance Increases Expected. Changing the design to add capabilities that were not part of the initial design concept and therefore not explored during prototyping may limit the value of the information gained during prototyping. Again, this condition relates to the need for an austere, focused prototyping effort in which the information generated is used to inform specific decisions regarding design, requirements, and technology.

Conclusions

A careful application of prototyping can result in significant benefits to a program, including reduction in technical risk and demonstration of technological feasibility, refinement of requirements, and more informed cost–performance tradeoff decisions. However, prototyping alone cannot ensure a successful program outcome; cost, schedule, and performance outcomes are affected by a range of factors independent of prototyping that may overwhelm any benefits gained through prototyping.

DoD's new acquisition policy mandates competitive prototyping at either the system or subsystem level prior to Milestone B.[14] Competitive prototyping is one specific kind of prototyping strategy involving two or more teams designing, constructing, and testing their respective system (or subsystem) and technology concepts. This type of prototyping strategy usually happens relatively early in the technology development phase of a program. The prototypes themselves are usually limited to demonstrating specific design concepts and technologies, and can provide information not otherwise attainable to inform the source-selection decision. This meets the definition of an austere prototyping strategy and satisfies the conditions discussed above as facilitating success. To the extent that the resulting information is properly used to inform program decisions at Milestone B, and no additional requirements or capabilities are added after the baseline is established, the policy may contribute to an improvement in program outcomes. However, recent experience represents a cautionary tale: The F-22, JSF, and LCS all included a competitive prototyping phase, and all have experienced cost growth and schedule slip.

There are several important caveats regarding the potential of competitive prototyping that acquisition officials should consider. First, the competitive aspect of this policy requires two or more teams with the requisite knowledge and capabilities at the system or subsystem level. However, consolidation in many sectors of the industrial base has changed the nature and value of competition.[15] In these cases,

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14 See DoD Instruction 5000.02, December 2008.

15 In particular, if there are only two firms (or teams) that can design and build a particular system or subsystem, and there is a formal or informal policy to maintain at least two, then competition is very different than it was in the past. Shipbuilding, manned aircraft and heli-

competition will not necessarily yield the benefits of innovation and of cost reduction and control that are usually expected.

Second, by mandating competitive prototyping in the technology development phase, DoD's policy may inhibit other prototyping strategies. The successful application of any prototyping policy requires that officials think through the goals, acquisition environment, technical characteristics, and needs of a given program to determine what type of prototyping makes sense. The policy mandate might result in officials forcing a competitive prototyping strategy into the design of a program when the characteristics of that program require some other approach to addressing risk. For instance, the demonstration of the military utility of a new concept or technology does not always require competition. The discretion and judgment of experienced program managers and oversight officials are important conditions for successful implementation of this new policy mandate.

Last, the lack of definitive evidence supporting the benefits of prototyping in general, and competitive prototyping in particular, is somewhat troubling. Existing case studies and statistical analyses present the policymaker with mixed results. As a result, DoD's new competitive prototyping mandate was incorporated into policy without a strong link between the new policy emphasis and its intended improvement to program cost, schedule, and performance outcomes. Does competitive prototyping really result in better outcomes? Under what conditions will competitive prototyping yield the desired benefits? What are the key lessons from past and more recent experience with competitive prototyping? How can the potential benefits of competitive prototyping be maintained in the face of all the other factors affecting program outcomes? A carefully structured analysis of prototyping strategies, with an emphasis on recent experience with competitive prototyping (e.g., F-22, JSF, and LCS), would help ensure a more successful implementation of the new policy.

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copters, and heavy armored vehicles are sectors where this concern is real. See Schank et al., 2006; Birkler et al., 2001; and Birkler et al., 2003.

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